CONSULTANT REPORT

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Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Buildings End-Use
Energy Efficiency

PERFORMANCE ASSESSMENT AND ADOPTION PROCESS OF AN INFORMATION MONITORING AND DIAGNOSTIC SYSTEM PROTOTYPE

Gray Davis, *Governor*

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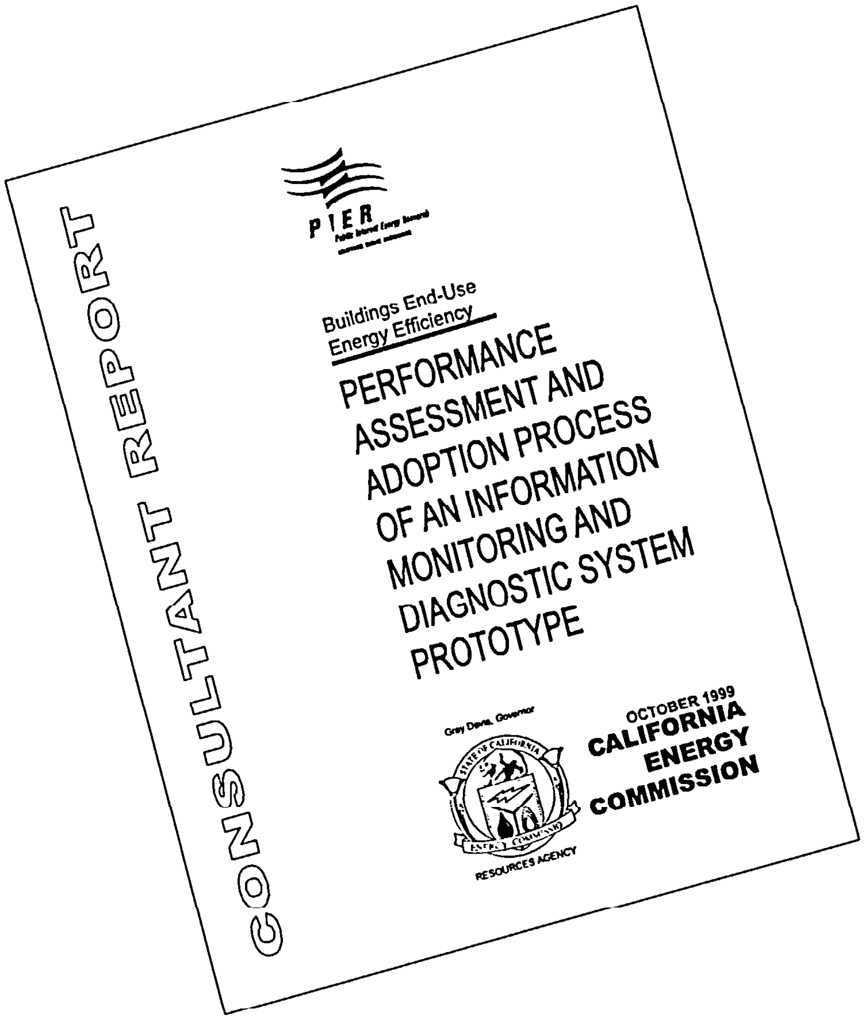

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Performance Assessment and Adoption Processes of an Information Monitoring and Diagnostic System Prototype, one of nine projects conducted by the California Institute for Energy Efficiency. This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Background

This report addresses the problem that buildings do not perform as well in practice as is anticipated during design. There are many reasons for this, including improper equipment selection and installation, lack of rigorous commissioning and proper maintenance, and poor feedback on operational performance, including energy performance. Few tools are available to the on-site engineer to address these problems, which results in excess energy use and higher operations and maintenance costs. A related problem is that existing Energy Management and Control Systems (EMCS) used to monitor building performance are becoming more complex over time and are difficult for the average operator to understand. Building operators typically have only monthly utility bills to track how much energy is used, and EMCS have limited data collection, archival, and visualization capabilities, and have few techniques to extract relevant information from the data. Thus, some automated diagnostics capability is needed to inform an operator when there is a problem or deviation from normal operation. Furthermore, most EMCS do not include energy monitoring in their scope; thus operators have no feedback on the performance of key energy-consuming equipment.

This report summarizes the third phase of a multi-year project that began in late 1992. The goal of this multi-year project is to develop, introduce, and evaluate state-of-the-art information technology to enhance building energy performance by continuously improving operations and maintenance (O&M). The research team has developed and deployed a prototype Information Monitoring and Diagnostic System IMDS, which consists of 57 measurements with high-quality sensors, and 28 calculated points that monitor the performance of building systems and outdoor weather. These data are archived each minute, and are available for analysis with a sophisticated data visualization tool, which includes a remote, web-based capability. This report summarizes research conducted during 1998 and 1999 in commissioning and operating this prototype IMDS installed in a 100,000-square-foot office building in San Francisco.

Technical and economic objectives were to:

- Maintain, enhance, and finalize the IMDS specification
- Evaluate the IMDS performance
- Develop and demonstrate techniques to automate fault detection and diagnosis
- Evaluate decision making and technology adoption processes in the commercial buildings sector
- Evaluate the costs and economic potential of IMDS

Approach

The approach used was to partner with an innovative building technical manager who is responsible for over 100 commercial buildings. The research team has developed and deployed a prototype IMDS, which consists of 57 measurements with high-quality sensors, and 28 calculated points that monitor the performance of building systems and outdoor weather. These data are archived each minute, and are available for analysis with a sophisticated data visualization tool, which includes a remote, web-based capability. To evaluate the IMDS, we interviewed the Technical Manager and Chief Engineer approximately every two weeks. We also used a computer model of the chillers to assess model-based fault detection techniques. The automated diagnostics research included exploration of evolutionary programming techniques that match monitored data to standard models for visual display. The project uses a technique called Participant Action Research in which researchers monitor the decisions and actions of their industrial partners in response to the technology as it develops. We have also conducted a series of interviews with other operators to obtain their feedback on the IMDS.

Findings

The IMDS has successfully operated during the entire year with a small amount of data loss during the first few months of commissioning and has been well received by the building's Technical Manager and Chief Engineer. These building operators value being able to continuously archive key building performance data for analysis using higher quality graphics than those typically available. They recommend that similar technology should be adopted in other buildings. They also recommend that the data be available remotely using the Internet and web-based data visualization tools.

The IMDS has shown the building operations staff a series of critical control problems that they did not know existed. They believe they would find similar problems in other buildings. We have not achieved the 15-percent energy savings from building tune-up activities that are often possible with such technology; however, the IMDS has been used to solve control problems and improve overall comfort. The automation of the controls has been improved greatly, freeing up time for the staff to take care of other tenant needs. The air distribution system in the building has been balanced, potentially improving health, comfort, and productivity. The reduction in labor-hours required to operate the building as a result of the IMDS is worth about $20,000 per year. These savings would pay for the IMDS in about five years. The operations staff expects to see even greater savings as they proceed with a control retrofit planned using the IMDS. The research team presented the operations staff with a series of recommendations for actions to achieve additional energy savings, some of which will be adopted over the next year. Overall, they expect to reduce energy use by more than 20 percent over the next year, saving more than $30,000 per year.

The main conclusions of the model-based fault detection work are as follows. First, relatively simple, steady-state models can be used as reference models to monitor chiller operation and detect faults that cause a significant degradation in performance. Transients associated with variations in the loads on the chillers can be removed from the data using a simple digital filter. Simple empirical models, such as the polynomial curve fit model used here, are undemanding computationally and can be implemented easily on-line for use in real time or off-line for periodic batch processing.

Work in automated diagnostics related to evolutionary programming concluded that evolving automatic plot readers to detect arbitrary patterns in plots could be done with current technology. A prototype stand-alone building data analysis tool was developed to provide the operations staff with additional capabilities beyond the IMDS. The operations staff does have data analysis interests and needs of this sort. They utilized other analysis software and used Fourier transforms to analyze fan power oscillations. This exploration demonstrates the need for more power building data analysis tools.

Sensor accuracy, reliability, and data acquisition sampling rate have been a major issue in the project. The results of the fault detection work indicate that the ability of the IMDS to measure cooling load and chiller power to one-percent accuracy with a sampling interval of one minute permits the detection of faults that might otherwise go undetected. The measurement of power and thermal loads at the one-percent level is also desirable for performance contracts, since profits can be significantly affected by undetected degradations in performance at the one-percent level.

This research evaluated two types of technology adoption processes, radical and routine. In the routine adoption process, the managers report that they identify routine adoptions by certain characteristics. The most important of these is that a routine innovation is almost always an enhanced feature of an existing product that is already well understood. Managers prefer to put every product into the routine process and seek to persuade the asset managers and owners that costs for the upgrades are known, expected and have been budgeted. Technical managers remind the financial decision-makers early and frequently about the need for the upgrades to reinforce the need for the new technology. Payback calculations are important and routine innovations are subject to rigorous scrutiny. The source of information about routine innovations is almost always from vendors and trusted industry users who have experience with the product. This research indicates that studies, which involve enhancement of features to an existing product, should include a vendor partner.

In the radical adoption process, technical managers use a different process. Using the vision and knowledge that stems from their own experience, the managers introduce the radical technology into their organizations without using the rigorous payback criteria found in routine innovations. The opportunity to learn about a new and promising technology, even if it is expensive and its potential paybacks are unknown, is so compelling that the managers decide virtually by themselves to proceed. The most frequently cited reasons for the adoption is the desire to learn about new technologies and stay ahead of peers. Control of the new technologies is important to innovative technical managers. Managers attempted in every circumstance to have the radical innovation tested at the building that housed their own office. We conclude that studies that involve radical innovation can be effectively tested using an approach where researchers partner directly with innovative technical managers. A direct approach allows innovative new ideas to be developed on customer sites without facing the rigorous payback calculations early in the technology development process. The radical technology in this research has been fully adopted by the pilot study users. In particular, they plan to adopt various aspects of it in their other buildings.

Recommendations

This research project has found the IMDS to be of significant value to building operators. We provide the following recommendations to outline both technical research and deployment research required to further understand and foster the development of the technical approaches considered in this study. The general recommendation from the overall evaluation of the IMDS is that significant improvements in building performance data measurements, archival, and visualization are needed to support operations staff. The IMDS is a high-end tool to support building operations.

Further research is needed to explore how to best utilize these techniques given the current suite of EMCS and related tools available to operations staff.

- Develop and demonstrate the IMDS in additional sites
- Enhance and extend model-based fault detection
- Evaluation of long-term benefits

In addition to these specific recommendations related to the IMDS, the conclusions of the radical and routine innovation research suggests that researchers and research program managers should attempt to partner with industry innovators. Such partnerships help to ensure that research activities result in technology that will be more readily accepted by practitioners.

Abstract

This report addresses the problem that buildings do not perform as well as anticipated during design. We partnered with an innovative building operator to evaluate a prototype Information Monitoring and Diagnostic System (IMDS). The IMDS consists of high quality measurements archived each minute, a data visualization tool, and a web-based capability. The operators recommend similar technology be adopted in other buildings. The IMDS has been used to identify and correct a series of control problems. It has also allowed the operators to make more effective use of the building control system, freeing up time to take care of other tenant needs. They believe they have significantly improved building comfort, potentially improving tenant health, and productivity. The reduction in hours to operate the building are worth about $20,000 per year, which could pay for the IMDS in about five years. A control system retrofit based on findings from the IMDS is expected to reduce energy use by 20 percent over the next year, worth over $30,000 per year. The main conclusion of the model-based chiller fault detection work is that steady-state models can be used as reference models to monitor chiller operation and detect faults. The ability of the IMDS to measure cooling load and chiller power to one-percent accuracy with a one-minute sampling interval permits detection of additional faults. Evolutionary programming techniques were also evaluated, showing promise in the detection of patterns in building data. We also evaluated two technology adoption processes, radical and routine. n routine adoption, managers enhance features of existing products that are already well understood. In radical adoption, innovative building managers introduce novel technology into their organizations without using the rigorous payback criteria used in routine innovations.

1.0 Introduction

1.1 Problem summary

Buildings rarely perform as well in practice as anticipated during design. There are many reasons for this, including improper equipment selection and installation, lack of rigorous commissioning and proper maintenance, and poor feedback on operational performance, including energy performance. A recent evaluation of new construction commissioning found that 81 percent of the building owners surveyed encountered problems with new heating and air conditioning systems (Hagler Bailly Consulting, 1998). Another study of 60 buildings by LBNL (Piette, et. al., 1994) found that half were experiencing controls problems, 40 percent had HVAC equipment problems, 15 percent had missing equipment, and 25 percent had energy management systems, economizers, and/or variable speed drives which were not functioning properly. Such problems are widely reported in the building commissioning literature (PECI, 1998).

Systematic procedures to address these problems are beginning to emerge. For example, research at Texas A&M University has found that in almost all older buildings, and even in many new buildings, the use of the building is quite different from the original plan (Claridge, et. al., 1994). These researchers use a monitoring process of “continuous commissioning” to tune building systems for optimal comfort and peak efficiency based on current operational requirements. Their methods have saved an average of over 20 percent of the total energy cost (over 30 percent of the heating and cooling cost) in over 80 buildings (Claridge, et. al., 1994). While these researchers have demonstrated success in bringing in experts to “fix” building systems, few tools are available to the on-site engineer to conduct such improvements.

A related problem is that EMCS are becoming more complex over time and are difficult for the average operator to understand (Hyvärinen and Kärki, 1996). Furthermore, most EMCS do not include energy monitoring in their scope. Building operators have only the monthly utility bill to help track how much energy is used. One study that supplied building operators with energy use data found that after a few months of strong enthusiasm, building operators lost interest in standard energy use plots provided by the utility research project (Behrens & Belfer, 1996). Building operators need assistance in sifting through the large volume of data available with new monitoring technologies. Current EMCS have limited capabilities in collecting, archiving, and displaying important building performance data. We pose the question of whether higher-quality data are needed to perform important analysis. New techniques are needed to assist operators in extracting relevant information from the underlying data. Thus, some automation of diagnostics is needed to set off alarms that can tell an operator when the diagnostic system has identified a performance problem or deviation from normal operation.

This research also addresses the variations in the professional activities of building operators, including their knowledge and technical sophistication. The vast majority of research in the fault detection, commissioning, and diagnostics area has focused on using expert engineers as the analysts, rather than working directly with building operations staff. Controls companies report that building operators are not interested in analyzing large, complex building performance data sets. This project has specifically addressed the question: is there a market for high-quality, high-resolution, archived building performance data if the tools required to simplify the analysis are also provided? Finally, this project addressed the problem of understanding how property management companies identify and analyze new technologies. Are these processes similar from company to company?

1.2 Purpose of report

The purpose of this report is to summarize the past year's research in commissioning and operating a prototype Information Monitoring and Diagnostic System (IMDS) demonstrated in a 100,000-square-foot office building in San Francisco, referred to as the Hong Kong Bank Building, also known as 160 Sansome Street. This report also provides a brief review of previous year's research results since the project began in the mid-1990s (Sebald and Piette, 1997; Piette et. al., 1998). The IMDS was installed in May of 1998. The report focuses on the research from September 1998 through August 1999. Another objective of this report is to disseminate findings and accelerate adoption of IMDS technology.

1.3 Project goals and objectives

The broad goal of this multi-year project is to develop, introduce, and evaluate state-of-the-art information technology to enhance building energy performance by continuously improving operations and maintenance (O&M). This project also involves both market pull and market push goals to accelerate the adoption of the technology. Both of these goals include some market assessment activities. In the market pull area, the research team seeks to evaluate the decision-making process by building operations staff and understand what motivates them to accept or reject new technology. Another overarching goal is market transformation. By advancing state of the art technology, we hope to help push the market toward greater overall performance. Further, we intend that our work will facilitate future market-pull initiatives by illuminating the decision-making criteria and processes of building operations staff. By examining the whole process of technology development and adoption, we seek to identify specific points for market intervention and targeted research. Our intention is to provide a template that will allow for the development of partnerships between businesses and researchers to mutually enhance the knowledge of the entire team. We also seek to inform providers of this technology of the findings from our research since we seek to influence the evolution of these monitoring and diagnostic systems. A final technical goal is to develop strategies that advance the technology from a passive monitoring system to an automated diagnostic system, taking advantage of emerging computational capabilities. Five specific objectives of the past year's research efforts were to:

1. **Maintain, enhance and finalize the IMDS specification.** The initial IMDS specification was developed prior to the selection of the building and was used to present the technology concept to the prospective demonstration site partners. During the past year we have made some changes to the software.
2. **Evaluate IMDS performance.** To evaluate the energy savings and other non-energy benefits of IMDS use in technical terms. Our aim was to reduce total energy use and energy cost by 15 percent without sacrificing any other building services or performance issues. Energy use in most commercial buildings is dominated by electricity use; energy costs are dominated by electricity costs.

3. **Develop and demonstrate techniques to automate fault detection and diagnosis.** Although the project has focused on supporting and evaluating the usefulness of the manual, human-based diagnostic tool (IMDS), we have explored two approaches for automating fault detection and diagnosis. One is a steady-state chiller model. The other is evolutionary programming for self -learning systems.
4. **Evaluate decision making and technology adoption processes in the commercial buildings sector.** The objective of this aspect of the project is to provide a description of the innovation adoption process and a road map for the adoption of practical, business applications of new energy technology in the commercial building industry, focusing on the role of third-party property managers.
5. **Evaluate the costs and economic potential of IMDS.** In this report we ask the simple question, "What is the economic value of the data?" While there is no simple answer, we examine this question in detail, from a variety of perspectives.

1.4 Project phasing

This report summarizes the third phase of a multi-year project that began in late 1992. Further details on the phasing are presented below under "Project approach". Phase One results are reported in Sebald and Piette, 1997. Phase Two results are reported in Piette et. al., 1998. This project began at the same time that the early Internet browsers, such as Mosaic, were starting to be used. The project was conceived by CIEE to explore the technical and economic potential of emerging monitoring and information technology for commercial buildings. The operators at the building did not even have email. In contrast, this report discusses some of the tremendous benefits that the explosion of information technology has demonstrated to the building operations staff at 160 Sansome Street.

1.5 Summary of expenditures

This project was conducted using a total budget of $350,000 from the California Energy Commission, as listed in **Table 1-1**. These funds cover the monies used by researchers at Lawrence Berkeley National Laboratory (LBNL), Shockman Consulting (for Christine Shockman, a doctoral student at Stanford University), Supersymmetry, and University of California, San Diego (UCSD).

Table 1. Project spending by task

Task no.	Task name	Task budget
1	Revise work statement, task deliverables, and budget	N/A
2	Prepare quarterly progress reports	N/A
3	Maintain and enhance IMDS	$150,000
4	Functional specification	$50,000
5	Prototype review	$50,000
6	Test automated diagnostics	$50,000
7	Technology transfer	N/A
8	Prepare interim report	N/A
9	Prepare final report	$49,000
10	Final meeting	$1,000
	Total	$350,000

N/A = Not applicable

1.6 Background

1.6.1 Technology concept

In this section we present an introduction to the Information Monitoring and Diagnostic System (IMDS) and fundamental concepts in fault detection. The IMDS consists of a set of high-quality sensors, data acquisition software and hardware, data visualization software, including a web-based remote access system. The IMDS is a prototype system in that we have deployed a unique combination of sensors, hardware, and software to examine its value in a controlled test. The IMDS could be built up from individual components and installed in any commercial building. It is, however, a high-end system, intentionally designed for reliability, accuracy, and speed in data retrieval.

The IMDS is oriented toward deploying the basic infrastructure for an advanced information system. This demonstration will allow the controls industry to examine the value of such systems that greatly exceed today's current EMCS technology. Such a system is the starting point for more advanced, automated diagnostics, such as those based on fuzzy logic or neural networks. The system is a distributed data collection and analysis system. The primary elements of the system are:

- A monitoring and data acquisition system that measures 57 physical and 28 calculated points using high-quality sensors, including points typically not available from an EMCS
- A PC that stores the data and houses the data visualization software (Electric Eye)
- An ISDN line connecting the system to the remote researchers and the Internet
- A web server that is a real-time analysis tool demonstrating a small fraction of the larger set of data visualization capabilities.

The data are stored in a flat-file system, with remote data archives appended each day locally and remotely at LBNL. We are testing the first PC version of the graphics software, which was previously only available for use with high-end graphics workstations. Data from each sensor are archived in the PC server at the demonstration building. The data acquisition and graphical analysis software are located on the PC, allowing the on-site operator and chief engineer direct access to the data.

The IMDS development in Phase One included creating nine standard plots available for viewing of key performance data. The operations staff was trained to interpret these plots. The IMDS also offers a series of more sophisticated browsing and statistical analysis tools. These more sophisticated tools will likely be of greater use to the remote researchers. Researchers in several locations will have access to the data, plus the identical analysis software, allowing them to analyze the building performance and test the automated diagnostic systems. The PC server will offer a subset of the real-time analysis graphics from the demonstration site to the public over the World Wide Web. The purpose of these graphs is to demonstrate the technology to interested organizations and potential service providers such as energy service companies, utilities, and control companies.

Figure 1 shows key elements of the system.

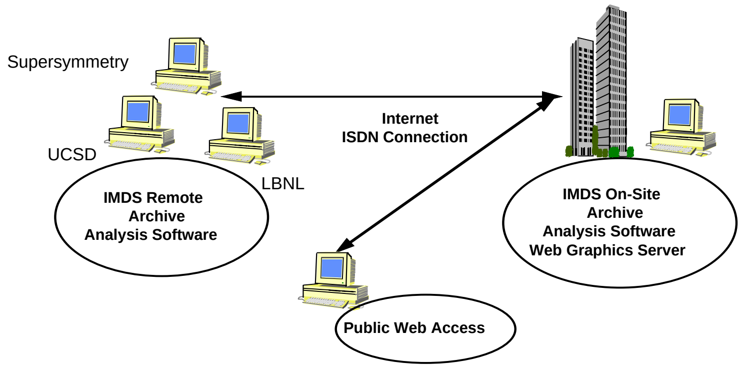


Figure 1. Components of the Information and Monitoring Diagnostics System

Four types of measurements are taken by the IMDS: temperature (including wet-bulb), electric power, flow speed, and pressure. The installed system consists of 57 physical and 28 calculated points for a total of 90 points sampled at one-minute intervals. The sensors include high-grade thermistors, electric power transducers, magnetic flow meters, and aspirated psychrometers to measure relative humidity.

Table 1 summarizes the monitoring scope. Further details of the sensors and sensor accuracy were presented in Piette, et. al., 1998.

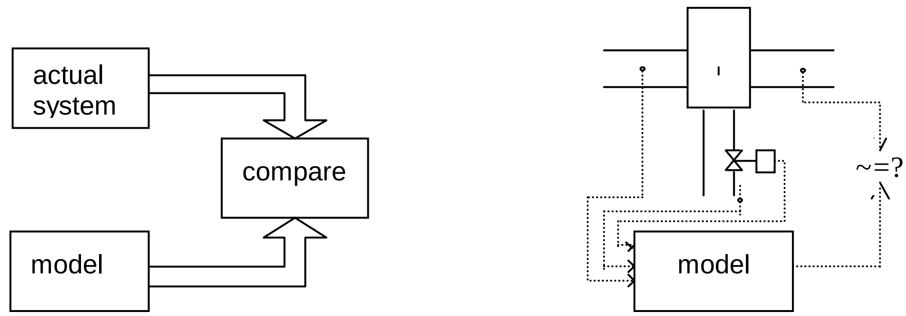
Table 2. Systems and sensors in the IMDS

System to be evaluated	Measurement	Number of physical points
Whole building	Electric power	1
Two chillers	Differential pressure (water) Water temperatures Flow rates (water) Electric power	4 8 5 2
Four pumps	Differential pressure (water) Electric power	4 4
One cooling tower	Dry bulb temperature Wet bulb temperature Water temperatures Electric power	2 2 6 2
One air handler	Dry bulb temperatures Electric power Static pressure	5 2 4
Local micro-climate	Dry bulb temperature Wet bulb temperature	1 1
Miscellaneous (lights & plug)	Electric power	4
Total		57

The IMDS is designed to be permanently installed and continuously active. This is necessary because buildings continuously change. For example, some problems recur, such as those from modifications to schedules to handle special events. These modifications often lead to equipment being left on when not needed. The diagnostic system is designed to operate in parallel with an existing EMCS, rather than expanding or modifying the EMCS. The IMDS is therefore not constrained by EMCS data collection capabilities, which can be problematic with 50 points of one-minute data. This technology may, however, be incorporated in future EMCS. The EMCS at 160 Sansome focuses on scheduling and controlling building HVAC systems including air temperatures and flows and monitoring zone conditions. By contrast, the IMDS measures energy, weather and waterside variables (temperatures, pressures, and flows).

1.6.2 Automated fault detection and diagnosis

Fault *detection* is the determination that the operation of the building is incorrect or unacceptable in some respect. Fault *diagnosis* is the identification or localization of the cause of faulty operation. “Diagnostics” is a broader term, encompassing both fault detection and fault diagnosis. Since fault detection is more straightforward than fault diagnosis, automation of fault detection is a logical first step in providing a fully automated system. Automating fault detection but not fault diagnosis is appropriate in buildings where there is a competent operator who wishes to be informed of the existence of problems but wants to take responsibility for determining the nature of the problem and the appropriate action. Model-based fault detection involves the comparison of the measured performance of the actual system to the expected



performance, as predicted by a reference model of the system (Figure 2).

Figure 2. A model-based fault detection scheme

The left hand diagram in Figure 2 shows the general principle and the right hand diagram shows the application to a heating coil, in which the inputs to the model are the inlet temperatures and the control signal and the output of the model is the outlet air temperature.

Reference models used for fault detection can be either qualitative or quantitative. One common form of qualitative model is a set of IF/THEN rules, which would be implemented in a knowledge-based system, together with an inferencing engine. There are two main types of quantitative models: first-principles and empirical. Two common methods of implementing empirical models are polynomial curve fits and neural networks. In each case, the model is only as good as the data used to train it; training data that cover the operating range of interest are required, since empirical models generally have poor extrapolation properties.

If the reference model is a steady-state model, i.e. it does not treat dynamic response, it is necessary to use only steady-state data, both when training the model and making comparisons between measurements and model predictions. Various forms of steady-state detectors have been employed in automated diagnostics; a summary is given in Hyvärinen and Kärki, 1996. In the terminology of the reference, the detector employed here is based on the geometrically weighted average of the functional variation. This average is calculated recursively and is given by:

$$\overline{V}_k = \alpha \, | y_k - y_{k-1} | + (1-\alpha)\overline{V}_{k-1}$$

where y_k is the value of signal at sample-time k and α is the forgetting factor ($0 < \alpha < 1$). The signal is deemed to be in steady state when $\overline{V}$ is less than a selected threshold, t.

1.6.3 Technology innovation theory

Emerging technologies are not adopted by an entire population simultaneously. Within any population there are individuals who are inclined by background, education, personality and temperament to seek out and examine new technologies and ideas first. They represent a small but critical part of any population and are termed *innovators*. Innovation researchers have broken down populations into five ideal types that are identifiable across many types of innovations, industries and populations (Figure 3).

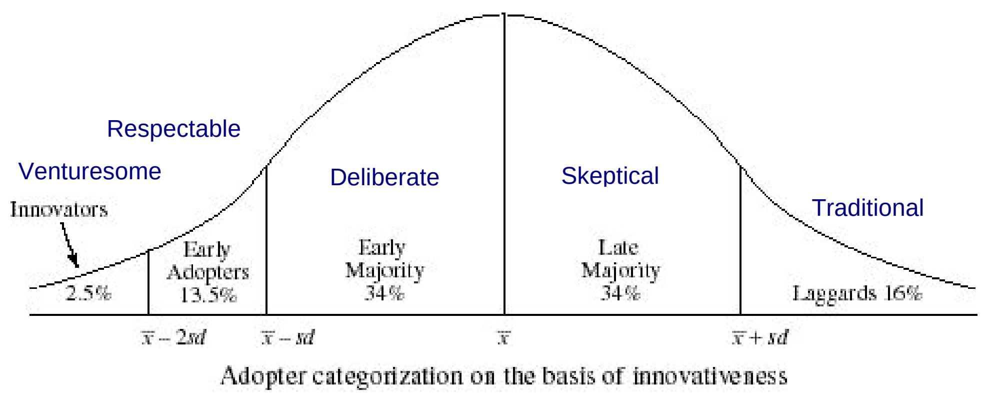


Figure 3. Ideal types of innovators found in any typical population

The estimated percentage of the population in each category of innovation is shown (Rogers, et. al., 1983).

It is rare that any substantive innovation enters a population without first passing through innovators and early adopters. Frequently, there is a break, between the adoption by early adopters and adoption by the early majority, where products and services die (Moore, 1999). Innovators and early adopters will look at more technologies than the wider population and will discard some innovations. The first and critical step in developing an understanding of the adoption of any technology is to understand who the innovators are. Innovators act as gatekeepers for technologies within their own companies. These innovators are easily identified by others in their industry even though they are not formally appointed (Allen & Nochur, 1992; Tornatsky, et. al., 1983). The adoption processes described in this report are separated into two main categories: routine innovation and radical innovation.

1. **Routine innovation** – Routine innovations are generally innovations to existing products. This innovation can be large (new chiller systems) or small (hand-held tools). This method of adoption is frequently used and the introduction of these types of innovations does not change the way that the company does business.
2. **Radical innovation** – This type of innovation is sufficiently unique to the prospective user that he or she must first understand how it fits into his or her existing business. While it may share key features with other technologies, it must be sufficiently different that its introduction changes the way the company or building operates (Dewar and Dutton, 1986).

The adoption process includes several stages:

1. **Knowledge.** The prospective user becomes aware of the innovation.
2. **Persuasion.** Users follow up on their original information to determine if the innovation suits their needs.
3. **Decision.** The user decides to adopt or reject the innovation.
4. **Implementation.** The innovation is put into place and the adopter gains first-hand experience with the technology.
5. **Confirmation/denial.** The now-experienced user determines whether the innovation is suitable for their purposes and determines a course of action.

While the stages of the adoption process are artificial constructs developed by the researcher to categorize events in what is really a continuous process, they are standard among industry users and with minor variations are commonly used in innovation research (Rogers, 1983).

1.7 Project Approach

This project was carried out in three phases.

Phase One included an investigation and evaluation of diagnostic methods, tools, and techniques. Our analysis considered issues such as sensor and communications technology, bottom-up versus top-down diagnostics architecture, and the design of temporary versus permanent systems. We examined the status of techniques from the field of intelligent systems (e.g., artificial intelligence, fuzzy logic, and neural networks) and diagnostics used in process control industries. We identified innovative building operators and chief engineers in major metropolitan areas who were recruited to give us direct feedback on what they thought were the most serious problems in commercial buildings. A 50-page questionnaire was administered as part of a full-day interview with six individuals. The interviews concluded that there was no single outstanding problem that would define the priority area for diagnostics research. Rather, the problem was related to a lack of good information about the performance of their building overall, and the problem of poor information from the EMCS.

During Phase Two, the building was selected for a case study, and the system design was finalized and installed. A review of the building energy use and initial findings from the IMDS during Phase Two are reported in Piette et al, 1998.

Phase Three addressed the five objectives through the research activities described below.

Maintain, enhance, and finalize the IMDS specification – All of the data were examined for completeness on a regular basis. A series of problems were identified and corrected. The final specification is available on the web at http://poet.lbl.gov/tour/.

Evaluate the IMDS performance – The operations staff was interviewed every two weeks to determine how they had been using the IMDS. These discussions included evaluating the performance of various building components and system. The IMDS was installed in May 1998. We used data from May and June as a baseline to evaluate the performance of the building. This evaluation was done to ensure that we had at least a few months of observations prior to fully training the on-site staff in the IMDS operation. The building staff began using the IMDS on a daily basis in late summer 1998. We have collected all of the data and examined them for completeness. A detailed analysis of the multi-year energy use data was conducted to examine whether there have been any energy savings between July 1998-June 1999 and the previous year.

Develop and demonstrate techniques to automate fault detection and diagnosis – This project has included chiller modeling for model-based fault detection and development of evolutionary programming techniques.

Model-based fault detection for chillers – The general approach for using a model-based fault detector for a particular HVAC subsystem is as follows:

1. **Select the model.** Select the type of model to be used as a reference model (quantitative versus qualitative, first principles versus empirical, steady state versus dynamic).
2. **Tune the steady-state detector.** If the model is a steady-state model, set up a steady-state detector to indicate when the comparisons between the model and the real system are valid. This involves tuning the parameters of the detector so that it removes as many unsteady points as possible while not removing an undue number of steady points.
3. **Configure the model.** If the model is an empirical model, obtain training data from the real system when it is known (or assumed) to be operating correctly. These training data are measurements of the inputs and output(s) of the model taken from the real system. Ideally they should cover the operating range of interest. The best way to obtain these training data is from a systematic functional test procedure, of the sort used in commissioning. This ensures that data covering the whole operating range are collected over a short period of time, before the system has had a chance to degrade or be modified, and allows the data to be compared easily with the manufacturer's performance data. For empirical models, the configuration process involves fitting the model to the training data, usually using some form of least-squares procedure. The standard deviation of the residuals provides a general indication of the goodness of fit and hence of the adequacy of the model structure. A more appropriate test is to examine the points with the largest residuals and determine if there is any objective reason why they should have been excluded *a priori*. If not, these residuals determine the threshold for the fault detector, since they result from what are deemed to be valid measurements from a correctly operating system.
4. **Implement, monitor.** Use the model to monitor performance and test for faults. This monitoring can either be done in real time, with the model running on-line and making comparisons sample by sample, or it can be done off-line at suitable intervals, e.g., every day.

Evolutionary programming research on automated diagnostics – During Phase One, which took place during the mid-1990's, the research team developed the IMDS concept based on interviews with innovative building operators. The IMDS design would include accurate, high frequency data collection with a top-down design. The top-down design would provide performance data for the whole-building, major systems (e.g., cooling plant) and sub-systems (such as chillers and cooling towers). The IMDS would compare the measured data with benchmark data from simulations, rules of thumb, or models of correct performance. and operators could be. One of the concepts of the IMDS is that rather than trying to detect specific faults, the system was specified to monitor performance in areas of the building that were performing poorly. The intent was to tell building engineers: "There is something wrong with subsystem X," rather than, "The front bearing on pump 6 is failing." The IMDS was designed with the concept that once building operators are made aware of a problem in a specific subsystem, they are reasonably good at tracking it down. The principal advantage of using human-based diagnostics is that one can immediately generate useful detectors for potential efficiency increases. By partnering with actual building operators, we can progress in an orderly fashion toward increased specificity without running the risk of missing "big-picture" issues.

Consistent with the overall project objectives, the UCSD team had the specific objective of interfacing an analysis prototype with the real data and so provide a means by which the building operators could investigate the data, have access to benchmark data sets and readily available plots. A demonstration system, implemented in Matlab, was developed that has a rudimentary capability to learn from real data. (Matlab is a mathematics and data analysis program commonly used in academic institutions. The idea was that the operators would make some specification such as, "On such and such a date and time, X was fixed." and the automated system would learn by example and create a test to determine whether data presented to the system indicated that X was fixed or faulty. This would be done for problems the operators consider important and frequent enough to require automatic detection.

In the development of the evolutionary programming techniques and the decision to use graphical approaches to extract information from the IMDS data, a method is needed for generating filters which automatically recognizes specified patterns in the data and alert the operators when such detection has occurred. The patterns were to be specified in advance (as opposed to the self-learning capability described below). These filters were of three types:

1. Range checks (potentially multidimensional)
2. Two-dimensional plots in which the axes were arbitrary functions of the raw data and regions to be detected were of arbitrary shape and not necessarily connected.
3. Three-dimensional plots in which the axes were arbitrary functions of the raw data and the regions to be detected were of arbitrary shape and not necessarily connected.

The UCSD diagnostics team explored these capabilities. A method was developed for automatically creating a robust test for a building condition that was important to operators and that could be generated from a statement from the operator such as, "X was fixed on -/-/- at ---- hours and – minutes." Such an on-line capability would also be able to obey operator commands, such as, "Let me know if the following condition recurs".

Evaluate decision making and technology adoption processes in the commercial buildings sector – The evaluation of decision making and technology adoption processes used Participant Action Research (PAR) techniques (Whytte, et. al., 1991). In PAR, the participants are informed about the research goals and objectives, and are allowed access to the research results. We have agreed to allow the industry participants to slightly conceal descriptions of their adoption processes to ensure full cooperation and obtain the most accurate representation of the processes. Results are provided that accurately represent the process while protecting the identity of the participants. The results are generalized and are not unique to any participant unless noted otherwise. All participants have agreed to be identified by company name for the purposes of this report. The subjects in this study are third-party property managers who specialize in operating commercial buildings they do not own. Third-party property manager's core business is the management, operation, and leasing of buildings. The companies who have participated in this research are:

- Jones Lang LaSalle
- Kennedy Wilson
- Cushman Wakefield (Northwest area)
- Cushman Wakefield (Southwest area)
- Pacific Properties Limited

The project tested the following three hypotheses regarding technology adoption processes:

1. Experienced innovative managers of commercial buildings have developed a way of identifying and analyzing new technologies. These processes may be generally well known to innovators in their industry, but no scientific research has been conducted to formally document the process.
2. The processes are sufficiently similar from company to company that there is a general adoption model that can be developed.
3. The adoption process for radical and routine innovations are sufficiently different to warrant separate discussion and model development.

The industry participants were selected by their peers in the Building Owners and Managers Association (BOMA). A general description of an innovator was provided to the BOMA local offices and they were asked to provide a list of ten companies in their local area that were innovators. A dialogue was opened with industry innovators in Northern and Southern California. The purpose of the dialogue has been to use the knowledge and experience of the industry participants to develop a technology that was useful and would desired by practitioners. Potential users have guided the selection of the IMDS technology from the earliest days. The technology was developed to overshoot commercial applications —that is, it was not intended to provide an incremental advance in the technology of building operation. In 1992-1993, researchers anticipated the development and adoption of Internet technologies, the continued integration of control devices in new products and the expected lower cost of instruments, software and hardware. In 1992-1993 the research team expected the monitoring system to evolve toward a system similar to the present IMDS. The IMDS technology was unavailable when this project began. It was not expected or required to be cost-effective as it is the subject of a research project.

Participants were made aware that the technology was experimental, costly and would not provide a traditional industry payback in the experimental stage. No promises of energy savings, operational savings or other benefits were made. The participants had to agree to participate without any guarantee of benefits.

Evaluate the costs and economic potential of IMDS – The economic evaluation included examining the costs to procure and install the IMDS. These costs were compared with operational savings. Statewide savings potential, assuming significant market penetration of the IMDS, was estimated.

2.0 Conclusions and Recommendations

2.1 Evaluation of project objectives

Overall, the project has been successful in meeting the specified objectives. In this section, we report on the key findings relative to each objective.

2.1.1 Maintain, enhance, and finalize the IMDS specification

The IMDS has been successfully deployed and maintained during the project. This third phase of the research project began with the commissioning of the monitoring system. The various sensors and associated recorded data were verified for correctness and validity. Where appropriate, sensor readings were compared to a secondary sensor reading. For example, the flow meter readings were compared to readings from a temporary strap-on ultrasonic flow meter. Where a deviation from expected values was found, corrective actions were taken. The full commissioning of all sensors took approximately five months. In addition to the sensors, the data acquisition system was commissioned. This system required several software setup changes and adjustments. By January 1999, all sensor and data acquisition systems had been fully commissioned and were working reliably.

Different aspects of the data acquisition system and data visualization software were upgraded during 1998-1999. The Linux operating system on the computer running the various data visualization software was upgraded, and several upgrades and maintenance tasks were undertaken on the data acquisition system, including replacement of some I/O and upgrades to the data acquisition software. The most important upgrade was to the data visualization software. Several new features were added to the software to make it easier for the building operators to access commonly viewed graphics. A bookmark feature was added giving the users the ability to set up a standard graph, bookmark it and return to that same graph without having to re-select the points and graph options. This feature was well received by the building operators and is used on a daily basis.

A full description of the system can be found at http://poet.lbl.gov/tour/. This description is a public-domain specification for use by potential end-users and service providers. A detailed binder containing the information from the web site was prepared for the on-site staff at 160 Sansome.

Table 3 shows the completeness of the data for July 1998 through June 1999. The data are 100 percent complete during the final four months of the analysis period. Missing data were related to point commissioning, power outages, air in pipes corrupting flow measurements, and other such factors. A detailed log of the commissioning activities was developed which can be used to guide the installation of future IMDS sites.

Table 3. Data completeness (percent missing) for all points

Folder (# of points)	1998						1999						
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Avg
AHU (10)	20	9	3	18	1	5	3	10	0	0	0	0	6
Chiller 1 (12)	25	51	13	12	1	5	2	10	0	0	0	0	10
Chiller 2 (12)	47	51	19	18	4	5	3	10	0	0	0	0	13
Tower (15)	27	20	5	12	1	5	2	10	0	0	0	0	7
Powers (11)	12	7	4	18	1	5	2	10	0	0	0	0	5
Pumps (10)	34	21	5	3	7	5	3	10	0	0	0	0	7
Stat Press (5)	100	100	100	80	5	5	5	10	0	0	0	0	42
System (8)	100	100	36	5	1	5	5	10	0	0	0	0	22
Weather (2)	100	100	6	3	1	5	5	10	0	0	0	0	19
Avg/point (85)	40	40	16	18	7	5	3	10	0	0	0	0	12

2.1.2 Evaluate the IMDS performance

There have been three primary benefits of the IMDS at 160 Sansome:

1. A dramatic improvement in the understanding and use of the existing control system, resulting in greater automation of the controls and a control redesign which will achieve energy savings over the next year.
2. A reduction in complaint calls and improved comfort, which increases tenant satisfaction and productivity.
3. Extended equipment life from reduced short cycling which is a result of the improved control and reduction of air in the chilled water system.

The project has successfully demonstrated a new technology that was extremely useful to the building operations staff at 160 Sansome in evaluating the building's performance. The building operators perceive significant improvements in the performance of the building. These include improvements in control, reduced comfort complaints, and the identification of significant energy savings. Even more significant is that the IMDS has been useful in identifying problems at the building that are related to problems inherent in the control systems themselves. These can only be remedied with an EMCS retrofit, which is being planned for the following year. The IMDS has played a major role in designing the retrofit. Furthermore, the new EMCS will be required to perform functions similar to those that the IMDS provides.

The following are features requested by the technical director for the new control system:

1. Abandonment of the “trend log” metaphor, replacing it with a “data archive.”
2. A graphical interface is not a picture of a fan or chiller system with readings attached, it is, instead, an x-y graph of system data; data to be selected “on-the-fly” by the operator.
3. Remote system access by any web browser, as opposed to software supplied by the vendor or (general-purpose) remote access software.

There have not been significant energy savings to date, as further discussed Appendix II. While we have not met the 15 percent savings objective, we have identified more than 15 percent in energy savings that could be achieved if the controls were properly functioning. The operations staff estimates they could reduce steam use by 50 percent (Table 4). They also expect chiller plant energy savings from reduced reheat. The original estimate from the operations staff was that the reduction in steam use would be similar in magnitude to chiller savings. For every British thermal unit (Btu) in steam savings, there would be an equivalent reduction in chiller energy. This estimate is approximately equivalent to the current chiller energy use based on a simple efficiency of one-kilowatt (kW) per ton. We have simplified the assumption to estimate savings equivalent to about half of current chiller energy use. Further details regarding the status and problems with the EMCS are listed in Section 3.0, Discussion.

Table 4. Current energy use and predicted savings from the proposed control retrofit

	Current EUI (kBtu/sqft-yr)	Savings (%)	Savings (kBtu/sqft-yr)	Absolute savings per yr
Steam	36.9	50	18.5	1.7 8 10^6 kBtu
Electricity	55.6	2.5	1.39	37,500 kWh
Total	92.5	22	20.0	1.84 10^6 kBtu

Note: Energy Use Intensity (EUI) is based on 92,000 square feet of net rentable floor space. Total gross floor space is 100,000 square feet.

Table 4 lists the seven most significant problems identified and remedied within the last year, including the data used, the resolution of data needed, and the primary benefits of the correction. The most significant correction has been the adjustments to the morning warm-up and supply air control. Prior to the IMDS, the operators had little feedback on the dynamics of the HVAC equipment. The current EMCS has limited trend-logging capabilities. Figure 4 and Figure 5 show typical days before and after the modifications to the supply air control. Because of a lack of understanding of the EMCS, the supply air was actually being controlled from the return air temperature. The actual EMCS program was misinterpreted. Only after more than six months of careful examination of IMDS data did the operations staff begin to understand how the controls actually functioned. While this may seem surprising, it is actually fairly common within the buildings industry; building engineers defeat and work around control systems that they do not understand. There were no drawings of control logic explaining how the controls worked.

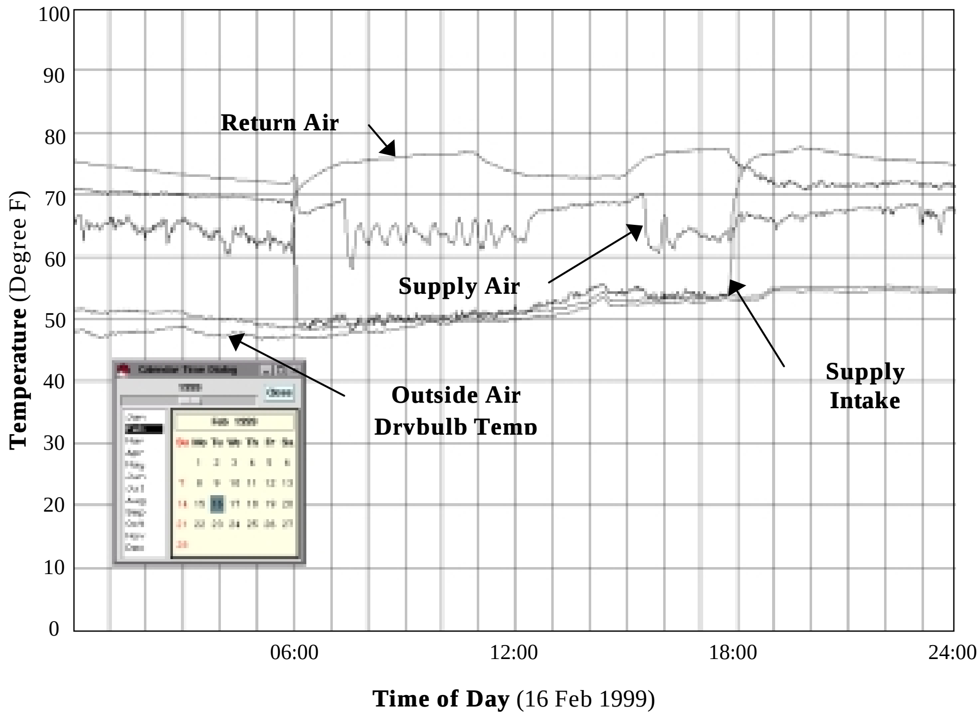


Figure 4. Supply air temperature with poor control

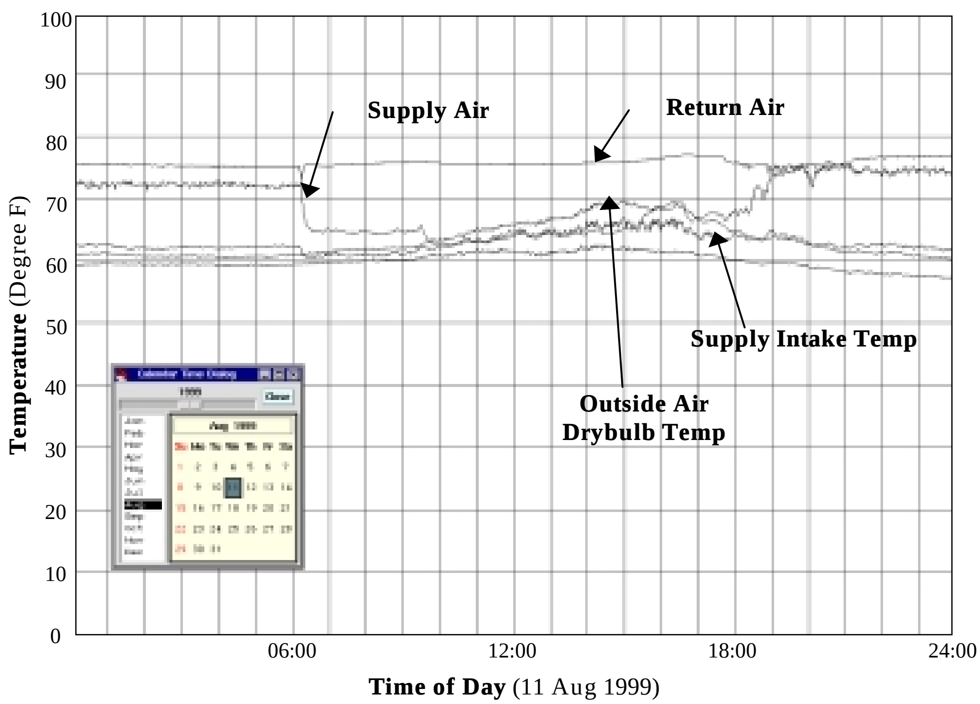


Figure 5. Supply air temperature with good control

Table 5. Problems identified and remedied with IMDS

Problem Description	Date Discovered & Fixed	Which Data Used	Resolution Needed	Benefits
Chiller false-start correction	D: May 2, 98 F: Over year	Chiller kW, Tons, Cooling Plant kW	1 minute	Avoiding false loading which could cause major chiller failure
Air in pipes	D: Sep 1, 98 F: Sep 10, 98	Flows, Tons	15 minute	Flow changed from 320 gpm to 580 gpm for Chiller 2, coils not starved now, improve pump life
Exhaust air re-circulating to towers	D: Nov 16, 98 F: Nov 16, 98	Return Air, Tower DB Temp	15 minute	Improve tower kW/ton
Morning warm-up tuning	D: January, 99 F: March, 99	Supply, Mixed, Return Air Temp, OSA	1 minute	Extend actuator life, improve comfort
Supply air tuning	D: January, 99 F. June, 99	Supply, Mixed, Return Air Temp	1 minute	Extend actuator life, improve comfort
Reduced fan power oscillations	D: February, 99 F: March, 99	Supply & Return Fan kW, Supply Air Temp	1 second & 1 minute	Tightened belts to extend fan life, improve control and comfort
Reduce dual-pump operation	D: Oct., 98 F: March, 99	Pump kW, Tons, Chiller kW	15 minute	Reduces energy use, extends pump life

The result of these control improvements has been a reduction in complaint calls. The building operator initially reported that complaint calls had been reduced from twenty to three per month.

We followed up with this claim by compiling 16 months of complaints logged between December 1998 and May 1999. The data showed that the number of complaints varied from three to 21 per month. We did not see the reduction that was reported by the on-site staff. After showing these data to the operations staff we were informed that not all complaints were logged. Although we do not have concrete evidence from the complaint logs to support the belief that the building is more comfortable, the building management staff is confident that complaints have been significantly reduced.

It has become quite clear over the last year that there are significant problems with the chiller controls. The chillers often operate for short periods of time, cycling too frequently. This is one of the findings that is motivating the suggestion for a major controls retrofit. This is further described in Section 3.0, Discussion, below.

Figure 6 shows a recent problem with chiller cycling that would not have been detected without one-minute data. The problem occurred after a service technician made some modifications to the chiller inlet vane control. Figure 7 shows the same data using 15-minute average data. The building operator was shown this graph and commented that it would not have shown the problem. He further commented that although he would have found the cycling problem the next day, which would have been too long given the severity of the cycling.

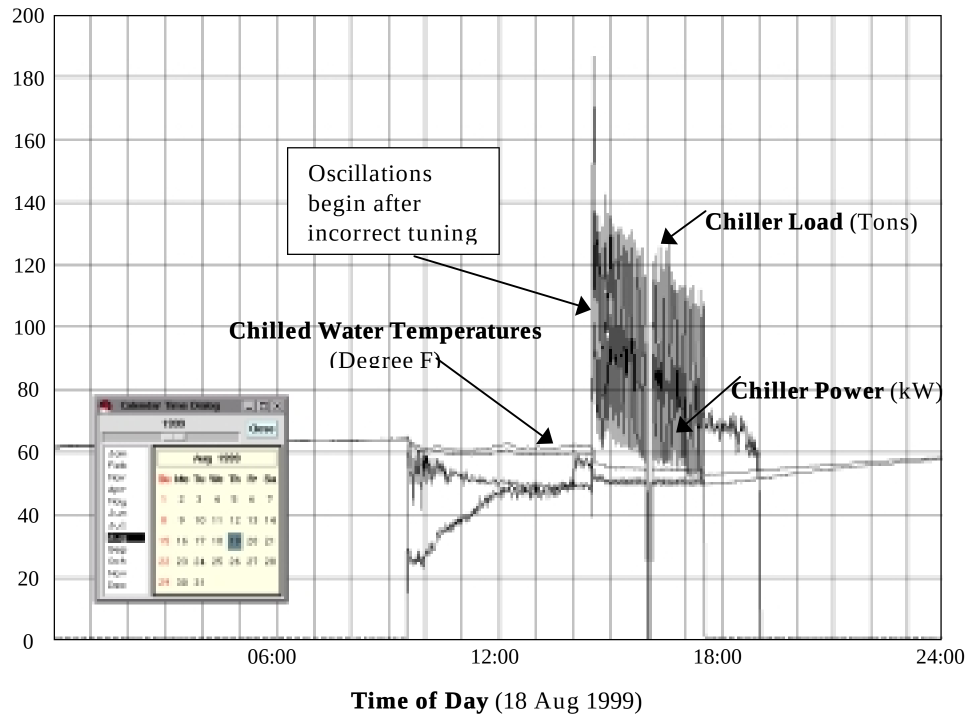


Figure 6. Oscillations viewed with 1-minute data

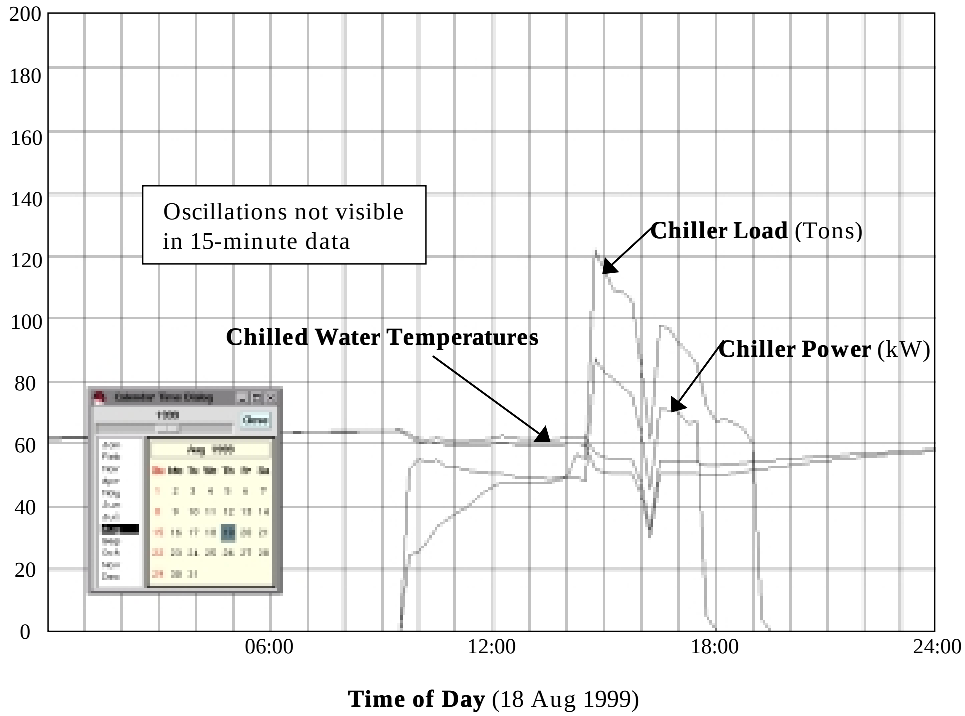


Figure 7. Oscillations not apparent using 15-minute data

In October 1998, a review of key findings from the first four months of data collection was presented to the operations staff and energy saving opportunities identified with the IMDS were discussed. The research team wanted to encourage the on-site staff to begin examining the data to evaluate the building performance. Table 6 shows results of this effort.

Additional details on the definition and assumptions for each of these estimates are found in Appendix I. This summary was presented to provide the on-site staff with examples of the energy savings opportunities present in the building. The savings from the fan VFD corrections represent the largest savings opportunity and may be implemented next year. The savings from running one pump instead of two have been achieved. The on-site operations staff is also pursuing the installation of VFDs on the cooling towers. Some of the other suggestions may not be implemented because of operational difficulties. The operations staff, for example, is reluctant to lower the chiller condenser temperature because this may create too low of a chiller pressure.

Table 6 Potential savings analysis, presented to operations staff October 1998

Summary of findings	Type*	One-time costs ($)	Annual energy savings (kWh/yr)	Annual cost savings* ($/yr)
1. Lighting and plug loads				
1.1 High nighttime plug loads	O&M	0	68,600	6860
1.2 High early evening lighting	O&M	0	29,400	2940
2. Chillers				
2.1 Retrofit chillers w/ 100-ton chiller	R	30,000	26,000	2600
3. Cooling tower				
3.1 Lower condenser water temperature	O&M	0	20,000	2000
3.2 Run cooling tower water without fans	O&M	0	11,190	1119
3.3 Install VFD's on cooling towers	R	10,000	22,380	2238
3.4 Reduce condenser side pressure drop	O&M	0	10,000	1000
4. Pumps				
4.1 Run 1 chilled water supply pump	O&M	0	6270	627
4.2 Trim chilled water pump impellers	O&M	1000	7010	701
5. Fans				
5.1 Modify duct /return to exhaust fan	R	50,000	223,800	22,380
5.2 Tune VFD on supply & return fans	O&M	0	122,360	12,236
TOTALS				
O&M - Low cost change & O&M	O&M	1000	274,830	27,483
R- Retrofits	R	90,000	272,180	27,218

*The costs savings estimates are conservative because we have used a simple, fixed cost of $0.10 per kilowatt hour (kWh) with no demand charges. Actual average electricity costs are higher, and vary based on peak demand costs.

As mentioned, in addition to the energy savings opportunities identified, the IMDS has been used to improve the use of the existing controls. The operations staff estimates that the operator spends significantly less time operating the building because the current system is now as fully automated as possible. The IMDS has freed up time to provide other services to the building tenants. The staff estimates a reduction of labor-hours of about 20 percent, equivalent to about to about 416 hours per year, or about $20,000 per year. The operations staff can pursue other activities that provide value to the building, including billable tenant services. One significant activity that has occurred as a result of the additional time for operations is balancing of the air system. The operations staff has balanced the airflow on each floor, which has contributed to the improved comfort and decrease in complaint calls. A $20,000 per year savings from the IMDS is equivalent to a five-year payback on O&M savings independent of the forthcoming energy savings. Furthermore, comfort improvements may have significant effects on the productivity and health of office workers in the building (Fisk and Rosenfeld, 1997).

The importance of sensor accuracy is related to what one does with the data. The data have been most directly valuable to the operations staff in tracking and evaluating how the controls function. In general, most of the problems identified and remedied by the operations staff could have been diagnosed using lower quality sensors. Identifying most of the problems did require the high frequency (one-minute) data archive. The required measurement accuracy for diagnosing problems may be determined by using the data in a model. As described in the following section, the ability of the model to predict power within three percent would require measuring both load and power to between one and 1.5 percent. Piette, et. al., 1998 provides a detailed discussion of the IMDS sensor and calculated point measurement accuracies for full and part load conditions. Measuring load to one percent requires measurement of flow rate to 0.5 percent and chilled water flow and return temperatures to about 0.01 degrees Fahrenheit (F), assuming a temperature difference of 5 degrees F. The IMDS measures flow to 0.5 percent for Chiller One. Chilled water temperatures are measured to an accuracy of 0.008 degrees F, meeting the 0.01 degrees F requirement.

2.1.3 Develop and demonstrate fault-detection and techniques

The main outcomes of the model-based chiller fault detection work are:

- Relatively simple, steady-state models can be used as reference models to monitor operation and hence detect faults that degrade performance.
- The transients associated with variations in the loads on chillers need to be removed from the data used to drive a steady state model in order to achieve reasonable sensitivity and a low false alarm rate. These transients can be removed using a simple digital filter.
- The operating data required to train an empirical chiller model typically takes several months to collect. Training an empirical model with data from a limited operating range results in a model that has poor accuracy outside that limited range. The longer the period over which data are collected, the greater the uncertainty as to whether the state of the chiller is constant over the whole period. The ideal solution is to collect the training data as part of a functional test procedure in which a wide range of operating conditions are induced artificially over a short period of time. This would reduce the likelihood that the chiller degrades significantly during the test and facilitating comparison with the manufacturer's performance data. The requirement for a comprehensive set of training data is reduced in PG&E's CoolTools™ package by providing a library of curves generated previously from comprehensive data sets and matching these curves to the available data.
- Simple chiller models derived using CoolTools™ can predict power within 15 percent and may, with care and some refinement of the CoolTools™ package, be able to predict within three percent. In the latter case, there is a need to be able to measure both load and power to between one and 1.5 percent in order to take full advantage of this prediction capability. Measuring load to one percent requires measurement of flow rate to 0.5 percent and chilled water flow and return temperatures to about 0.01 degrees F, assuming a temperature difference of 5 degrees F. Comments on how this relates to the IMDS are described below in Section 3.0, Discussion.

- Simple empirical models, such as the polynomial curve fit model used here, are undemanding computationally and can be implemented easily on-line for use in real time or off-line for periodic batch processing.

2.1.4 Evolutionary Programming Diagnostics

The overall conclusions of the evolutionary programming diagnostics effort are:

- Automatic plot readers to detect arbitrary patterns in plots can be generated using evolutionary programming.
- Sophisticated building engineers can use accurate, rapid sensing information coupled with the data visualization tools to increase their understanding of how their building works. Once convinced, they could utilize automatic detectors of anomalous behavior on a day-to-day basis. They are unlikely to use black-box detectors if they do not understand them.
- Competent building engineers are interested in comparisons with other buildings and in measures of maximum achievable performance.
- In order to understand the implications of measured data, sophisticated building engineers require a data-mining environment in which they are convinced of the accuracy of the data. In more complex systems, this requires a sophisticated operator/system interface capable of letting the engineer visualize the data in unforeseen ways to follow hunches or hypotheses or chains of evidence. Once the engineers understand what is going on (i.e., the data and their mental models are consistent), they could order automated tests. Data mining experts can assist in suggesting evidence chains (e.g., graphs) and automatic detectors.
- Competent building engineers have complex internal models of how their building is supposed to work and what areas are most critical to achieving building performance.
- The concept of frequent, accurate, and detailed data coupled with advanced data mining tools is revolutionary in the field of buildings operations. It changes the way one manages buildings and deals with maintenance contractors. Neither the tools nor the utilization techniques are mature at this point. The paradigm shift associated with being able to understand building performance in detail, and provide evidence to vendors when problems occur, warrants additional research and practical efforts from building operations staff.

2.1.5 Evaluate decision making and technology adoption processes

The key conclusions for the innovation adoption research is that building managers who have offered to adopt the IMDS technology use a significantly different adoption process from what is required of routine innovations. Routine innovations such as feature upgrades appear to be optimally targeted to the vendors rather than the technology managers. Vendors then present the technology to the technology managers. Radical innovations can be taken directly to the technical managers. The technical managers evaluate technical issues and translate the technology into financial terms and guide it through the adoption process. They can bring into a company technologies that are high cost, risky, do not have conventional payback calculations and not even completely understood by themselves. The motivations for adopting a promising radical innovation are self-described as “personal” with the major personal goal being the need to stay on top of the newest technology in their industry. This does not mean that the company gains nothing from the new technologies; obviously a more knowledgeable manager is a better decision-maker on new technologies.

2.2 Evaluate costs and economic potential

During Phase Two, the IMDS was installed for about $63,000, including hardware, software, and one year of ISDN service (Table 7). The cost of the installation of the instruments on the site was self-reported by the building staff at $23,000 to $25,000. The technical managers provided the hours and subcontract labor costs. We have used an industry standard $75 per hour for on-site labor that was provided by the technical manager. We believe the managers at the building have paid for some of the costs by “bolting the costs” on to other items. A 50 percent increase in the system installation cost results in a total cost for hardware, software, and installation of about one dollar per square foot.

Table 7. IMDS costs

System	Cost
Data acquisition system (EnFlex®)	$8,535
Computer system	$3,938
Sensors	
Cooling system	$31,860
Air handlers	$5,784
Building power	$3,916
Sensor Total	$41,560
Networking (ISP and 1 year of ISDN)	$8,912
Grand Total	$62,945

The on-site staff has shown great interest in the overall system, but are not inclined to support the use of high quality sensors used in the demonstration. They are, however, quite interested in the power and flow measurements available from the system, which are rarely available from an EMCS. Power measurements from dynamic systems, such as fans, chillers, cooling towers, plug loads, and lighting loads are of interest. The remote access, data archival capabilities, and high quality visualization tools are also features of great interest.

There are some good opportunities to bring the system cost down. The cost of each point in the IMDS at 160 Sansome can be found at http://poet.lbl.gov/tour/physpts.html. It is likely that any future IMDS would not use the calibration procedure that cost about $350 per thermistor.

The operations staff estimates that they will save approximately $30,000 per year with the control system retrofit planned for next year. This is based on reducing steam use by about half (worth $25,000), and reducing chiller energy use by about 37,500 kilowatt hours (kWh). Table 4 lists the energy savings. Details regarding the current status and problems with the EMCS are listed in Section 3, Discussion. Overall, the system is likely to payback over the next few years if the controls retrofit is complete and the savings from the fan VFD and the steam are realized.

The IMDS has not yet shown a payback based on energy savings. It has demonstrated that the technology is of significant value and the staff wants to continue to use such technology in other buildings.

2.3 Commercialization potential

This technology has demonstrated its value, although it is likely to be expensive in its current form. As mentioned above, the on-site staff is extremely interested in remote, web-based data archival and visualization tools. They have examined other software that claims to provide the same capabilities as the current system, but they have not found any other system with the same reliability. Several dozen commercial buildings industry representatives have toured 160 Sansome in the last year, including software developers, energy service companies, utilities, and researchers. There are a variety of building monitoring technology development activities that are being influenced by this demonstration. Control companies were not asked to participate directly in this project as it may have constrained the system; however, the controls industry and other potential building information technology service providers are part of the target audience for this technology.

2.4 Benefits to California if technology were commercialized

As described above, one objective of the IMDS demonstration was to save 15 percent of total energy use. This technology could reduce commercial sector energy use by 15 percent in typical large office buildings. Although this technology is applicable to large buildings in general, we have restricted this energy savings estimate to large office buildings in California. It is most likely that these buildings will be the first to utilize such technology given our technology adoption and deployment activities with third-party property managers.

The energy savings estimates presented here assume that 15-percent savings in electricity use could be obtained in both new and existing buildings using IMDS-type technology. Although these savings have not yet been achieved at 160 Sansome, even greater savings are expected over the next few years. While there will be some retrofit costs to modify the control systems, the controls will likely achieve greater savings than it would have without the IMDS. We estimate that these savings could penetrate the commercial sector (outlined in Table 8). For example, 30 percent of large offices could reduce their energy use by 15 percent by the year 2010. This is a fairly aggressive penetration scenario developed to demonstrate the technical potential this technology could achieve.

Table 8. Penetration rates for energy savings for new and existing buildings

Year	Existing buildings	New construction
2005	5%	5%
2010	30%	40%
2015	50%	70%

The statewide energy savings for large offices forecast growth in large office floor space by 2 percent per year with a project flat energy use intensity (CEC, 1998). Assuming the penetrations from Table 8 and the floor space projections in Table 9, we estimate that this technology could reduce statewide energy use by 2033 Gigawatt hours per year (GWh / yr) in Year 2015, worth $202 million per year.

Table 9. Statewide savings for large commercial buildings

	Current Practice (2000)	2005	2010	2015
Floor area (million ft^2)	969	1008	1104	1201
Business as usual consumption (Site GWh/year)	21886	22800	24695	26590
Electricity savings (site GWh)	0	115	1119	2033
Carbon savings (tons)	-	10,819	105,532	191,823
Dollars saved (electricity)	-	$11,443,622	$111,628,422	$202,903,918

While these energy savings are significant, the technology is likely to be adopted for non-energy benefits. This demonstration has shown that comfort is enhanced with IMDS-type technology. This could have far reaching affects on office workers, increasing productivity and health (Fisk and Rosenfeld, 1997). Improvements in equipment life and reduced maintenance costs are also likely.

2.5 Recommendations

This research project has found the IMDS to be of significant value to building operators. We provide the following recommendations to outline both technical research and deployment research required to further understand and foster the development of the technical approaches considered in this study. The general recommendation from the evaluation of the IMDS is that significant improvements in building performance data measurements, archival, and visualization are needed to support operations staff. The IMDS is a high-end tool to support building operations. Further research is needed to explore how to best utilize these techniques given the current suite of EMCS and related tools available to operations staff.

- **Develop and demonstrate the IMDS in additional sites.** Discussions are underway with the present operations staff and other building operations staff to demonstrate these concepts in other buildings. Such demonstrations will help identify how universal the 160 Sansome finding are, considering diverse factors such as the building operations staff, climates, and HVAC system variations. They will allow the assessment of radical adoption processes at additional sites with less innovative operators. The recommendations from the forthcoming report on the current Energy Commission PIER project, “Improve Cost Effectiveness of Building Control Systems,” will be incorporated into future IMDS specifications to verify their applicability to high-performance monitoring systems.

- **Enhance and extend model-based fault detection.** Further investigate current chiller models to evaluate operational discrepancies and hence improve fault detection sensitivity. Deploy current tool on-line and observe operator response to information provided by automated fault detection. Extend model to other components, including the cooling tower, pumps, fans, and cooling coil. Extend the steady-state detector to provide analysis of transients, such as detection of oscillations and power spikes.
- **Evaluation of long-term benefits.** Evaluate the energy savings of the controls retrofit at 160 Sansome stimulated by the IMDS. Examine the long-term acceptance and utilization of the IMDS. Assess persistence of operational improvements.
- In addition to these specific recommendations, the conclusions of the radical and routine innovation research suggest that researchers and research program managers should attempt to partner with industry innovators. Such partnerships help to ensure that research activities result in technology that will be more readily accepted by practitioners.

3.0 Discussion

3.1 Findings from the IMDS evaluation

One of the primary outcomes of the project has been that the information provided by the IMDS both stimulated and enabled the staff at 160 Sansome to undertake an in-depth analysis of its controls. A key finding has been that a significant control system retrofit is needed to properly operate the building. This section discusses these problems and provides further information about the building performance and how the IMDS has been used.

When the current staff assumed the management of 160 Sansome, all of the physical systems were manually operated. Over the last seven years they have made improvements in maintenance, but the information provided by the IMDS has allowed the operators to automate the building as fully as possible with the existing control system. The IMDS has also been used to evaluate the accuracy and limitations of the control system. The foundation of the current control system is the original equipment from 1966, which includes 120VAC (Volts Alternating Current) time-clocks, relays, and pressure-electric switches combined with standard 3 – 18 psi (pounds per square inch) temperature sensors. The controls provide start-stop control and lead / lag control for the chillers. There are no drawings of the relay wiring, PE switches, or pneumatic control drawings. Individual zone control on the floors was a traditional constant volume of air, with reheat at each zone.

In 1988 or 1989, a Direct Digital Control EMCS (DDC EMCS) was added. To reduce the first cost, the EMCS was interfaced to the relays, pneumatic actuators, and time clocks of the original system instead of directly controlling the chillers, fans, and pumps. Starting and stopping of the equipment is controlled both by time clocks in various locations and the DDC EMCS. The EMCS is comprised of a digital controller in the penthouse mechanical room and a 286 PC in the Chief Engineer’s office.

In 1991, a conversion to variable air volume began, covering ten of the 18 floors. Variable frequency drives (VFD’s) were added to the main supply and return fans, along with a fan control system using equipment from a different EMCS vendor. The fan control system provides start-stop control of the fans through the VFD’s. The EMCS energizes the fan motor starters through the old relay logic. To start the main fans, the EMCS first enables the motor control center (through the relay logic) to provide voltage to the VFD’s. The fan controller starts the fans by activating the variable speed drives. Neither control system communicates with the other, which means that both systems must be synchronized to provide start-stop fan control. There are four parts to the control system with problems. The costs for the repair and upgrade have been identified, as summarized below.

EMCS – The EMCS computer is a 286 PC, which is a weak link in the total system. The operators have seen four system failures over the last few years. The computer is irreplaceable and the software is not supported for year 2000 (Y2K) problems, but will operate. Replacement of the entire front end is required. The EMCS design was widely installed during the 1980’s. The programming is in its fourteenth revision. Because the front end uses a 286 PC, the vendor has only been able to use older software. This system cannot be expanded as desired. When the computer fails, it will require either finding a used computer for a partial solution, or total replacement of the entire EMCS.

Chiller controls – The retrofit of the control system in 1989 replaced the time clock to control the chillers. All temperature controls to start-stop and sequence the chillers and pumps are the original 1966 electro-pneumatic controls. Lead-lag switching of the chillers to balance the run-time and provide failure redundancy is hard-wired into the control system. As the building loads have decreased with the conversion of the 17th and 18th floors from a restaurant to office space, and the VAV conversion, cooling loads have been reduced. Seldom are both chillers needed at the same time. The accuracy of the chiller controls is problematic. The operators cannot set starting and stopping temperatures for the chiller plant within 2 degrees F. There are still old time clocks in the chiller control system that override the EMCS. The control system causes unneeded chiller operation and allows frequent cycling of the chillers (at up to twice an hour) adding an intolerable level of wear. The poor operation of these controls also causes excess energy use and poor temperature control. Upgrade of the chiller controls would cost approximately $10,000 to $15,000. A new, stand-alone, chiller control panel to provide plant optimization and sequencing would cost $30,000.

Heat exchangers – The building is heated by two heat exchangers controlled by two unequally sized steam valves. A manual change of the system piping is required for switching from summer to winter heating. Various settings must be changed in the EMCS after the piping change. The EMCS starts and stops the heat exchanger pumps on a fixed schedule. There is no outside air lockout. The temperature reset schedule must be manually changed at least two times per year. The operators would prefer to use a non-linear automated control sequence. The operators propose to add an overlay outside-air lockout to the heat exchanger. They have obtained a cost estimate for simple controls of both heat-exchanger valves (but no programming changes) of $3,500. Improvement of the temperature controls will require replacement of the software and the front-end EMCS.

Fan controller – The fan control system is also not totally functional. Of the three static pressure measuring points, at least two are in incorrect locations and do not provide usable readings. They are not easily moved because they are located in asbestos areas. The result is that the main supply fan runs at full power during all hours of operation (which is one of the most significant findings of the IMDS). Relocation of these sensors would be approximately $3,500. To make the fan control system Y2K compliant will require $1,374. In addition to energy issues, the fire control of the fans was never properly designed for an interface with the VFD's. There are multiple points for fan start-stop, which need to be integrated into the new fire-life-safety systems. This work will add additional cost to any piecemeal upgrades.

Summary – The cost to bring the controls to Y2K readiness and fix existing problems totals $60,000 to $80,000. A piecemeal upgrade would still suffer from poor reliability because of the complexity of multiple control systems, lack of drawings and schematics, and poorly supported hardware and software from multiple vendors.

Table 10 shows the previous list of problems along with a list of who discovered the problem, what the cause was, and if it would have been found without the IMDS. Most of the problems would not, and had not been identified prior to the IMDS. The on-site staff using the IMDS found most of the problems.

Table 10. Problems identified and remedied with IMDS

Problem Description	Who Discovered Problem	Type	Would Problem Have Been Found Without IMDS?	Cause
Chiller false-start correction	Glen S. and Kris K.	Control	Yes, but not as quickly	Recent work on controls done improperly
Air in pipes	Peter R., Kris K. and Glen S.	Cx*	No, problem existed for some time.	Air may have been present for many years
Exhaust air re-circulating to towers	Glen S. and Kris K.	Design	No, points weren't available previously	Design problem
Morning warm-up tuning	Fred S. and Glen S.	Control	No, points weren't available	Poor control settings, inability to evaluate controls
Supply air tuning	Fred S. and Glen S.	Control	No, points weren't available	Poor control settings, inability to evaluate controls
Reduced fan power oscillations	Fred S, and Glen S.	Maint*	No, points weren't available	Maintenance, perhaps design also
Reduce dual-pump operation	Saki K., Peter R.	Control	No, power measurements proved strategy was incorrect	Control logic not optimal

*Cx = Commissioning, Maint = Maintenance

It is important to identify which points and graphs have been most useful to the on-site staff so that future systems incorporate similar plots.

The most important points have been: Return Air Temperature, Supply Air Temperature, and Supply Air Intake Temperature. These are kept open on Electric Eye at all times during the day.

The next most common points they look at are: Outside Air Wet bulb and Dry bulb temperatures.

The plots that they have recently bookmarked include:

- Chiller One - Chilled Water Supply Temperature, Efficiency, Tons
- Chiller Two - Chilled Water Supply Temperature, Efficiency, Tons
- Chiller Two Complete – Chilled Water and Condenser Water Supply and Return Temperatures, Chilled Water and Condenser Water Flows, Tons, Power

The two most common XY Graphs are:

- Chiller One kW/Ton versus Ton
- Chiller Two kW/Ton versus Ton

Over the past year, they have also looked extensively at whole-building power and fan power. In fact, the staff undertook an extensive analysis of the fan power involving Fourier transforms to analyze some unexpected oscillations. These oscillations where greatly dampened after the fan belts were tightened. The IMDS was used to collect one-second data for a short period to assist in the analysis.

3.2 Techniques to automate the diagnostics

3.2.1 Model-based chiller diagnostics

Selection of the model – The model used in this study is the polynomial chiller model from the DOE-2 simulation program, as implemented in Pacific Gas and Electric's CoolTools™ package. The model takes the evaporator duty and the condenser water and chilled water supply temperatures as inputs and predicts the electrical power as its output. The CoolTools™ package facilitates the fitting of chiller models to performance data and allows these models to be used in a stand-alone version of the DOE-2 chilled water plant simulation. The chilled water plant simulation can be used to analyze system performance and address issues such as chiller replacement. CoolTools™ includes a library of curves derived from detailed measurements of the performance of a wide range of chillers. This library is used in cases in which a comprehensive set of measurements covering full load and part load operation is not available. In the case of 160 Sansome, the rated capacity of each chiller is 228 tons whereas the highest duty observed is less than 170 tons.

Setting up the steady-state detector – The steady-state detector was configured to monitor the evaporator duty, which has slower dynamics than the electrical power, due to the thermal capacity of the evaporator. Figure 8 is a plot of power per unit load (kW/ton) versus load (tons) for all the (minute) data for Chiller One. Inspection of time series plots showed that most of the outlying points are not in steady state. The steady-state detector was tuned by adjusting the threshold and the forgetting factor (α) until most outlying points were removed. Using a threshold of one ton and a forgetting factor of 0.1, all of the extreme outlying points were removed while at least 50 percent of the data were retained (Figure 9).

Configuring the model – Since the number of data points in the entire set of one-minute data is much too large for the CoolTools™ fitting procedure, the data were collected into bins, each bin representing a two-degree F range of condenser water supply temperature, a two-degree F range of chilled water supply temperature and a six-ton range of load. The values of each of the input variables and the output variable (electric power) were averaged for each bin and the resulting averaged values presented as training data for CoolTools™ .

Checking the model – To check the adequacy of the model structure, the model polynomial was applied to the entire set of data available for Chiller One (5/1/98 to 7/7/98 and 9/11/98 to 6/30/99). is a plot of predicted and measured power per unit load versus load. Investigation of the cluster of points with high measured power per unit load at about 45 tons shows that they correspond to sudden, isolated increases in power with no corresponding increase in load. Figure 11 is a time-series plot showing an example of this phenomenon, which is currently unexplained but appears to represent an operational fault of some sort. Otherwise, the model predicts the behavior of the chiller quite well, although there are some features in the plot of the measured values that are not seen in the plot of the predicted values, indicating that there are some effects present that are not treated by the model. The points that appear to have abnormally low power per unit load (between 110 and 130 tons) all represent measurements made on the day before the failure of the chilled water return sensor for Chiller One and are therefore suspect. A similar investigation was performed for Chiller Two using the entire set of available data (9/11/98 to 6/30/99). The chillers appear to have similar efficiency curves, though Chiller One has slightly higher efficiency.

Figure 12 is a plot of predicted versus measured power. It appears to show two populations at high power (greater than 100 kilowatts). These two populations are much less evident in the binned data used to train the model, suggesting the influence of an additional independent variable. In particular, the small set of points with a measured power around 105 tons and a predicted power of around 90 tons is currently unexplained. The question of the accuracy with which the model can be expected to predict power depends on whether this set of points corresponds to correct or faulty operation. If that operation is deemed correct, or at least acceptable, then the threshold for fault detection cannot be set lower than about 15 percent. If they are found, or assumed, to correspond to faulty operation, then the threshold could be set to about seven percent. If the modeling problems just discussed could be resolved, it should be possible to set the threshold as low as three percent, providing a much more sensitive fault detector. Both further, detailed, analysis of this data set and a study involving a number of chillers are called for to clarify the degree of model accuracy that can be expected in practice.

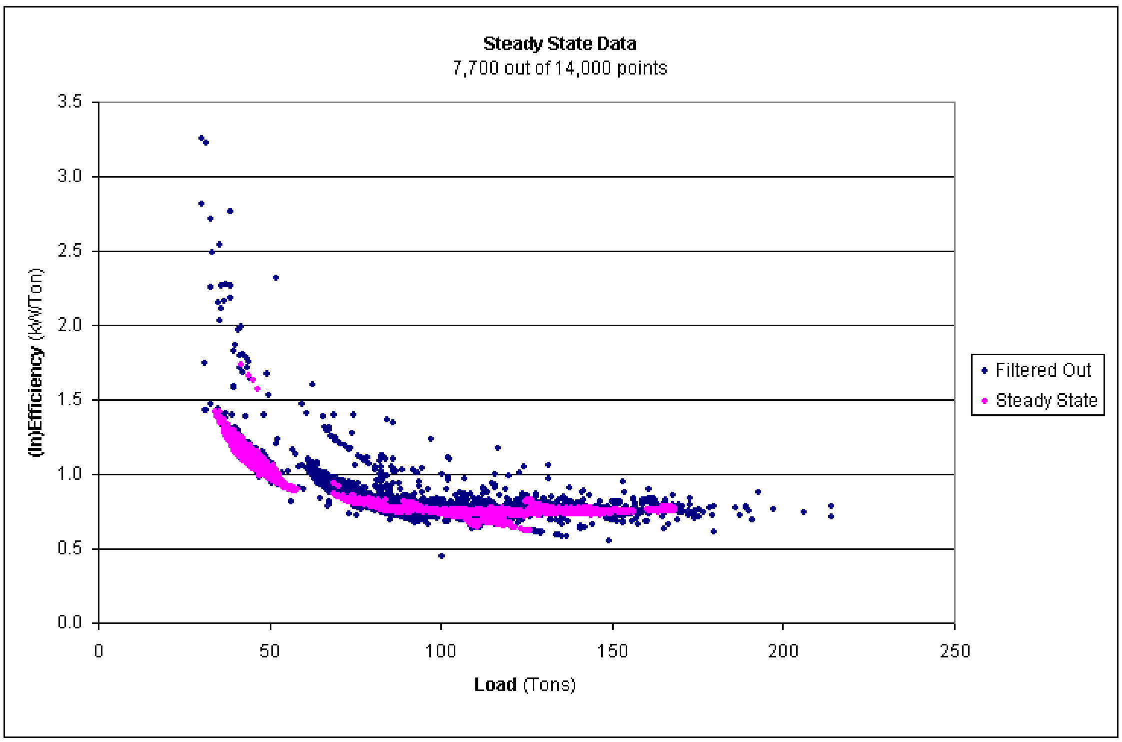


Figure 13 shows a comparison of the part load performance predicted by models fitted to the manufacturer's data and the measured data. Given that manufacturer's data typically takes maximum advantage of the measurement tolerances included in the ARI procedure for reporting performance, the agreement between the two is remarkably good. A similar investigation was performed for Chiller Two using the entire set of available data (9/11/98 to 6/30/99). The two chillers appear to have similar measured efficiencies, though Chiller Two is slightly more efficient.

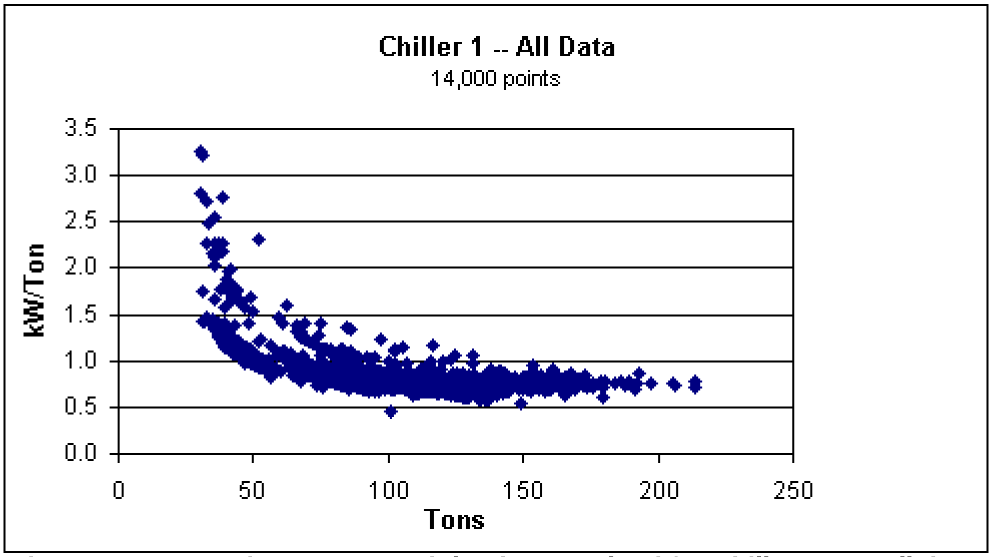


Figure 8. Measured power per unit load versus load for Chiller One – all data

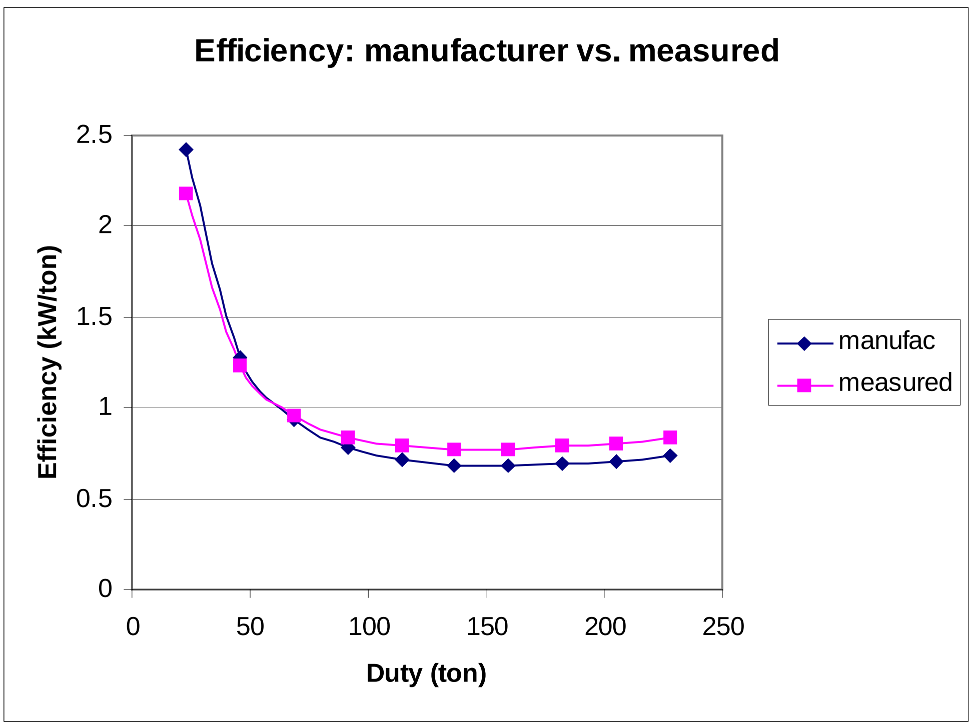


Figure 9. Measured power per unit load versus load for Chiller One – filtered data

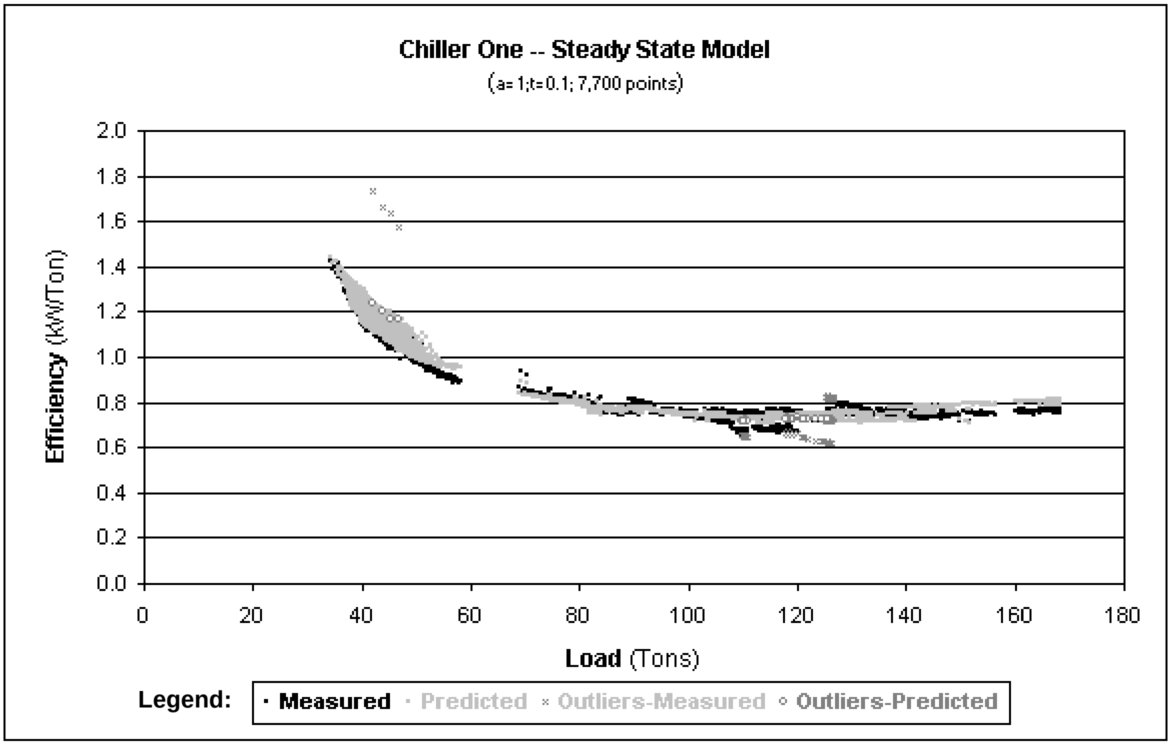


Figure 10. Predicted and measured power per unit load versus load for Chiller One – steady-state points only

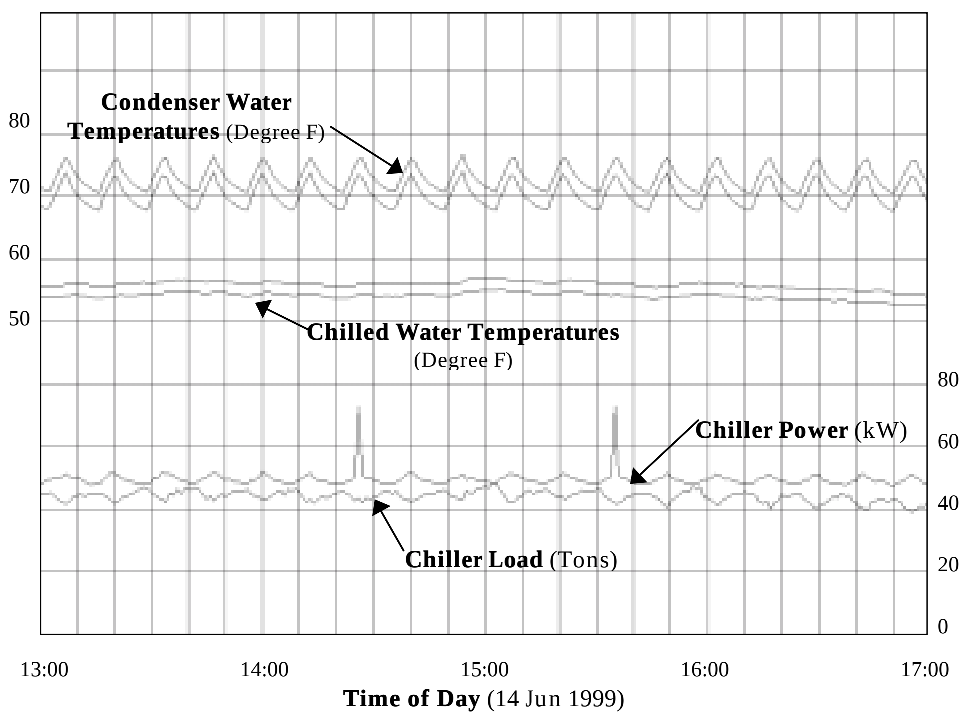


Figure 11. Measured values of electrical load and evaporator power for an occasion when a sudden change in power was observed (June 25, 1999)

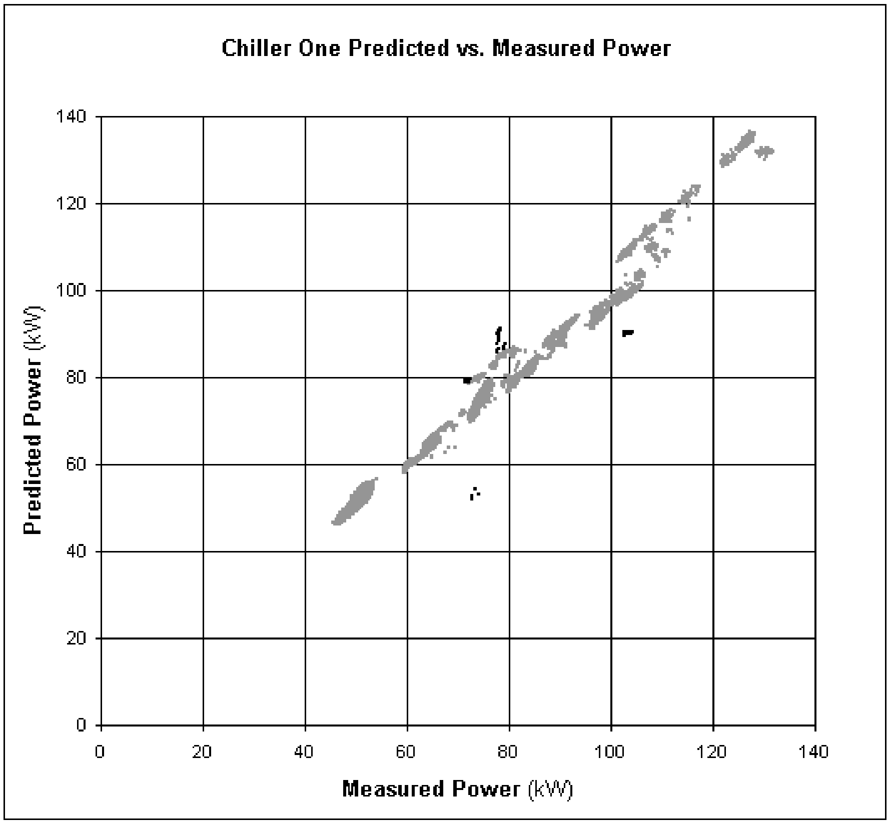


Figure 12. Predicted versus measured power for Chiller One

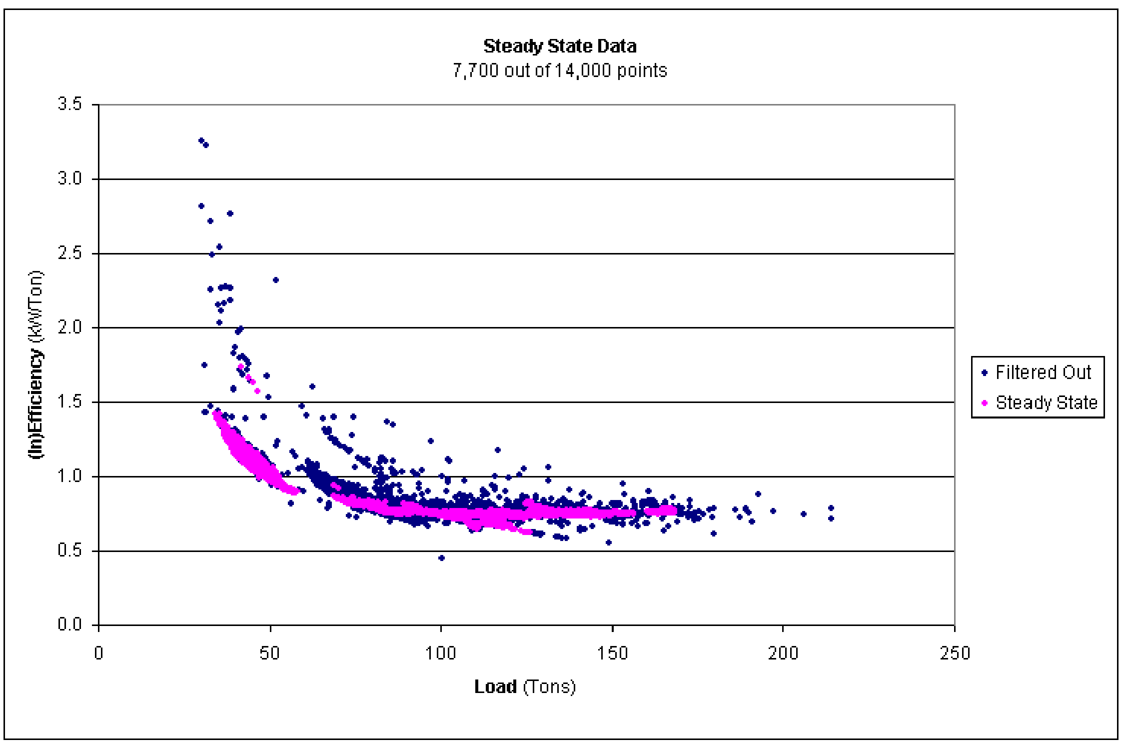


Figure 13. Comparison of the part-load efficiency predicted by models fitted to manufacturer's data and measured data

Model implementation – The steady-state detector and the chiller model are both simple enough they can be implemented easily, and without significant computational burden, either on-line in the EnFlex® data acquisition system, for use in real time, or on the computer running the data visualization software. In the latter case, they could be used either in real time or off-line for periodic batch processing.

3.2.2 Evolutionary programming

There were three kinds of results produced by the UCSD team: tool development, a prototype analysis tool, and building engineer comments. The UCSD researchers developed a tool to automatically read two-dimensional and three-dimensional plots. These were based on evolutionary programming techniques and are described in the "Theoretical underpinnings" section of the project Web site: http://vision.ucsd.edu/~kchellap/UCSDCIEE. These include development of techniques for autoreading and self learning. The Web site also describes the prototype system, which is comprised of several components:

- Total building benchmark comparisons of test building versus standard benchmarks:
  - Total building consumption benchmarks
  - Energy distribution (within building) benchmarks
- percent capacity chiller usage for each chiller
  - Examples of automatically read charts
  - Chiller kW/ton versus Tons chart
- Whole-building power carpet plot (three-dimensional)
  - Example of standard plots with range checks:
  - Cooling tower Return Water temp versus Outside Air Wetbulb
- Examples of range checks:
  - Supply Air Dry bulb Temperature
  - Cooling tower Return Temperature versus Outside Air Wetbulb

Given that the approach is graphically based and that both the automatic system and the operators need to be able to call up predefined standard plots, the web page also contains explanations of a MATLAB-based mockup of a data visualization system capable of providing operator- (or system-) specified plots with the click of a button. This capability was included in versions of Electric Eye for other computing platforms, but was needed for demonstration purposes before this capability could be included in the version of Electric Eye used in the project. This mockup was installed on a separate computer at 160 Sansome Street. The UCSD team discussed possible capabilities the engineers wanted in addition to the capabilities of the IMDS. These included:

- The ability to constrain data presented on a plot (e.g. to certain hours or to times when certain machines were running etc.)
- The ability to perform more sophisticated analysis, such as Fourier analysis, on selected data.

As predicted, the engineers were able to use the high quality sensing and Electric Eye's visualization capabilities to convince a control service provider that the system was not performing properly. Finally, given the difference in license costs, the engineers preferred MathCad to Matlab.

3.3 Decision making and adoption processes

This section provides additional details in support of the conclusions about the technology innovation concepts. The company that was the target of the IMDS pilot study will be described first. The industry participant’s company ownership has changed over the last two years as the company has been sold twice. It is now a part of Kennedy-Wilson Company, a company responsible for services in commercial buildings. The company’s office buildings are primarily in suburban and urban centers, and the majority are not staffed with an on-site engineer. The company typically staffs a building with an engineer if it is larger than 100,000 square feet.

All operators interviewed in this study are union members. These companies use the BOMA contracts for all engineering labor. Larger buildings have an on-site property manager responsible for accounting, showing the building to real estate agents and managing the building’s secretarial staff. As a fee manager, they have a fiduciary responsibility to act to the benefit of the owner and virtually all decisions about the properties are routed through the property managers to the asset managers and owners of the buildings.

The interviewees only bid for work they believe can be profitable. They do not recall an instance when they have bid a job below cost to gain entry to a large customer. They rarely fire the existing building engineer when a new building is acquired; instead they work with and enhance his knowledge. After an audit, they bring the building under manual control to determine how it must operate. They do not hire or work with a registered building engineer, subcontractor or control’s vendor to define how the building is to operate. All knowledge about building operation is experiential rather than acquired by a formal education. Using the existing sensors, equipment and hand controls, they get all the equipment under control without the automatic controls system. Next, they get the equipment under temperature control. After reviewing the operation manually, they try to determine how to operate the building better.

3.3.1 Peer participants and demonstration site innovator

The industry peers who have evaluated the technology and were interviewed for this project all work for large multinational companies that manage large portfolios of buildings. The management is sufficiently large to warrant the employment of technical experts at the corporate level.

The technical decision-maker at Kennedy-Wilson is Technical Coordinator Fredric Smothers. Mr. Smothers is responsible for more than 100 buildings totaling over 12 million square feet of commercial space. He describes his job as the technical translator for non-technical people and as the corporate representative for his company on technical matters. He represents the company in sales talks for new jobs and leads the technical adoption for the property managers within his company. Although he concedes that it is possible for technical changes to be adopted without his involvement, virtually none are. In addition to the engineering manager, he is also the troubleshooter for all of their buildings and he is called out whenever there is a technical problem in a building. Within his company, the organizational chart shows him above the property management personnel at the buildings, but this is somewhat misleading. His function is to serve as a technical resource person for the property management staff and he has a position parallel to the accounting department. That is, he is involved in every building in the portfolio, but only at the technical level.

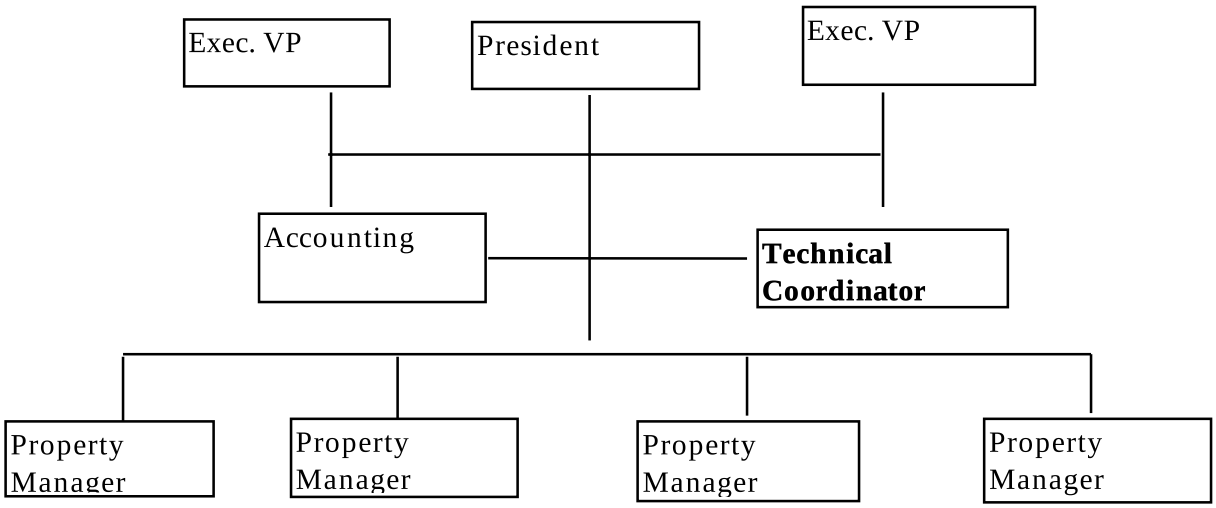


Figure 14. Company organization

Most of the people with whom Mr. Smothers deals with are not technical and have little interest in technical matters, since he is expected to take care of technical details. The management he works for want only to know whether the building equipment work correctly or if they should budget to repair or replace it. The company's on-site property managers are not in pursuit of high-quality systems, although the company is known for its technical expertise. (For example, San Francisco BOMA organization selected Mr. Smothers to head up their industry committee on deregulation, further confirming his status with his peers.)

3.3.2 Summary of the results from the routine adoption process

Routine knowledge – The technical managers were asked to select a routine adoption decision to focus their thinking about the routine adoption process. Selected products ran the gamut from new and expensive chillers to small, low-cost hand-held tools. The key feature of the product that the managers describe is that it is not something whose purpose requires understanding. Generally, the new products are upgrades to existing products, or replacements for worn out products that are already in the building. The managers are looking for more efficient, economical and reliable technologies for their upgrades. The routine adoptions frequently feature upgrades to an existing technology. The managers first see some products when they get a new building in their portfolio, either from new construction their company directed, or more frequently, from a building whose property management contract has been changed. These are comparatively less frequent than the routine upgrades that are done through their operating budgets.

Routine persuasion – For these managers, routine upgrades are not "black box" devices. They understand how existing products work and are familiar with any defects that product upgrades are designed to deal with. Products that fit into a routine adoption process are usually known in advance, and long term projections (of up to ten years) estimate the need for upgrades. Technical Managers describe their knowledge about upgrades as coming primarily from sales vendors. These vendors act in their own self-interest to describe features and enhancements. Generally, technical information is believable, cost paybacks and financial information other than cost are not. The vendors' self interest is considered to be a conflict of interest and while not unexpected, the managers seek to balance the information they have from the vendors with other information. The most desirable form of information is that which comes from the experience of a trusted peer. Managers have an extensive informal network for seeking out new information that has been developed over a lifetime of work in the industry. In addition to trusted peers, the managers also cite building engineers including those who no longer work for the technical managers. Professional design engineers are rarely consulted for routine innovations.

Routine decision – Products that are well understood and have a clear payback within accepted limits are more likely to be adopted. Others may be adopted depending upon ownership of a particular building. Managers refer to themselves as "unpaid salesmen" since as a part of their service to the clients they bring the best new technologies to the buildings they manage. The process of obtaining the owners decision to adopt is sometimes difficult as the property managers, asset managers and owners almost always have little technical background. Managers were asked to cite a routine innovation that they did not recommend that was subsequently adopted. None was able to provide a single example. Innovations that feature upgrades are subject to the technical manager's gate keeping.

Routine implementation – The managers were unable to recall an example where a routine innovation had difficulty in the implementation stage. These products are so well understood that few surprises occur.

Routine confirmation or denial – The managers had difficulty recalling cases of products that fit the routine adoption process that were subsequently denied. By definition the adoption of routine products rarely created any surprises.

Results for the routine adoption stage – Researchers seeking opportunities to enhance features and upgrade well understood products that are routinely adopted will be best served by working with vendors with a solid reputation.

3.3.3 Summary of results from the radical adoption process

Radical knowledge – Knowledge about our radical innovation came almost entirely from the research team. Unlike the routine innovation wherein innovations are so widespread that the process of determining were the information came from is difficult, the technical managers were limited in the radical adoption stage to the research team's descriptions of the technology. It is obvious that most of the participants did not understand how the technology worked and even more astonishingly, managers did not know what it was expected to provide that was different than technologies they had in other buildings. Paybacks were not promised and no information was provided to help them "sell" the innovation to their managers. Nevertheless, in contrast to the routine adoption process, the managers decided to participate early in the process even without full knowledge of the product, purpose or reward to their companies.

Knowledge about the specific details of the innovation seemed to be much less important to the user when discussing this radical innovation.

Radical persuasion – The adoption process for the radical technology is perplexing. The managers insist upon a nearly complete understanding of the routine technologies before they decide to adopt. By contrast, for the radical adoption, they are persuaded to adopt a significantly more complex and costly product that has an unknown result to anyone (even the researchers, although we at least have some intended results)! This perplexing attitude is taken to such extremes that in the selection of a potential site for a second IMDS project, the prospective pilot site managers were told by our industry participant (a trusted peer!) that the cost, installation time, and management time were greater than he expected, and that after one year, no direct financial rewards for the building had been realized.

Nevertheless, he suggested that they seek an opportunity for participation in a project site. His recommendation was sufficiently persuasive that we have lined up another pilot site participant for a future project. Several explanations present themselves. We first describe the interview results and then describe the results obtained by directly questioning the participants and asking for their insight.

During the interview process the managers from every prospective company selected the building that they were located in. Irrespective of the definition of the type of project, location, size or technology of the site desired by the team, they all attempted to persuade the researcher that the building that housed their office was the appropriate site for the technology. In one case they attempted to persuade the researchers to change the city of the pilot study site in order to move it back to the technical manager’s location.

All of the managers have gained a significant part of their power and their position from their mastery of technical information. The reasons described in the questionnaire are based on their “personal interest”. These managers hope to gain detailed information, background knowledge, and experience with what appears to them to be a promising new monitoring and information management technology. They are well aware of existing control systems and electronic devices and their shortcomings, defects and promise. They appear to be persuaded that EMCS technologies can be economically beneficial although they frequently have been disappointed in the commercial results. Controls technologies are promising but have never delivered completely adequate results at a reasonable cost. The opportunity to explore with the guidance of technically knowledgeable researchers seems to overcome many concerns.

Radical decision – None of the managers described great difficulty in persuading their asset managers, property managers or owners to adopt the new technology. All believed that they could put forward the proposal to their management and obtain approval easily. The decision to adopt the technology must pass through the organization for approval, but the managers were confident that they could get approvals. The adoption by others in the organization was seen as relatively easy and low risk. The key decision to adopt the technology appears to happen entirely in the mind of the technical manager. They seek little outside advice other than the research team. The decision to adopt is made quickly even before they understand all of the details of the technology.

Radical implementation – The implementation stage revealed some difficulties that were undisclosed at the beginning of the project. It became obvious that the entire company management did not understand the scale of the project. No contingency money had been set aside and some of the installation occurred at a slower rate than anticipated. The manager later reported that he had not informed the owner completely of the new technology, as he would not understand it technically. The property manager was equally uninformed and the researchers were cautioned to speak directly to the technical manager. While the upper management was unaware of the scale of the project, the technical manager and building chief engineer were fully involved. They contributed many extra hours and personal time to install and commission the IMDS. During the spring and summer of 1999 they claimed to be working about 20 hours per week on the research project and had begun to master the complexities of the software. This extended effort came after a slow acceptance of the IMDS. The manager and engineer had difficulty understanding the technical complexity of the system software although they had no difficulty comprehending the layout and purpose of the sensors. As they began to master the software and use the data, they began to pick up a variety of problems in the building. Their successes seemed to engender further interest and they now are enthusiastic users and supporters of the IMDS.

Radical confirmation or denial – Confirmation or denial is not easily defined. Generally, the evaluation of a technology based upon users simply reporting their satisfaction is less affirming than the situation where users take some specific action as a result of a new technology. The IMDS pilot study has resulted in some visible action. The primary action is the proposed major retrofit of the controls. The technical manager has obtained quotations to add control features to upgrade the IMDS and has discussed installing a portion of the IMDS system at another site. The lack of energy savings results to date has been disappointing, but the users clearly believe that the technology has great promise of saving energy in the future. One expectation from this pilot study was that the pilot study participants and the companies allowed the opportunity to see features in the pilot study would then request similar features in their purchases of future control systems. This situation appears to be happening with nearly every one of the persons interviewed. Of particular interest to the industry personnel is the way that the staff of 160 Sansome Street uses the data it acquires; that is, relying on real-time graphical data plots rather than on-screen schematics that report the system performance.

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Appendix I

Preliminary findings memo

Appendix II

Whole-building energy use analysis

Appendix I

Preliminary findings memo

To: Fred Smothers and Glen Starkey
From: Mary Ann Piette and Peter Rumsey
Cc: Kris Kinney, Chris Shockman, Tony Sebald, Satkartar Khalsa
Date: Oct. 28, 1998
Re: Findings from the Information Monitoring and Diagnostic System (IMDS)

As part of our research project with your building we have been examining the energy performance data collected to identify energy saving opportunities at the Hong Kong Bank Building at 160 Sansome Street. This memo outlines our key findings to date, along with recommended actions to reduce energy use. We have put these items in writing for you to review and would like to discuss them with you.

For each finding we have included a description of the problem, a conservative estimate of the energy saving and other benefits, and recommendations to achieve the benefit. Energy cost savings are based on a simple 10 cents per kilowatt hour. Your actual savings may be substantially higher. We have not included any potential peak demand savings.

Please note that these are PRELIMINARY ROUGH ESTIMATES and we look forward to discussing these energy saving opportunities with you in more detail. This is not an exhaustive list of all possible O&M and retrofit energy savings. We are still examining the overall energy performance of the building.

The building currently uses about 1,838 million watts per year (MWh/year), not including steam. We estimate O&M savings of about 275 MWh/year, which is about 15 percent of total energy use, as summarized in the table on the last page of the memo. These savings are similar to the level we predict can be found in most buildings with the type of information we have collected from the IMDS. In addition to the low-cost O&M savings, we have identified another 15 percent savings that can be achieved with more aggressive retrofits.

We hope that you are able to implement some of these recommendations while there is some cooling season left. When we discuss these savings possibilities with you, we will show you the data from the IMDS that were used to develop these energy savings estimates.

1. Lights, plug loads, and other

Finding 1.1: High nighttime plug loads

Description: The plug loads at the building are about 0.7 watts per square foot (W/sqft). While this is not high compared to other buildings, the nighttime load remains fairly high, at about 0.3 W/sqft.

Implications: Nighttime energy use is higher than necessary, and could be cut by about 0.2 W/sqft. These savings are equivalent to about:

0.2 W/sqft * 98,000 sqft * 3500 hours/year * $0.10/kWh) = $6860/year

Not only will this save energy, it will reduce cooling loads.

Costs to implement such a change are negligible with tenant cooperation, which we've been able to affect in other buildings.

Recommendation: Develop an information campaign for tenants to turn off unneeded equipment, such as computers, monitors, copiers and printers. Inform tenants about savings from enabling auto-power down features of Energy Star office equipment. This could be done with flyers, email, or a memo explaining the opportunity for savings. We are happy to help in this area. (See http://eetd.lbl.gov/EA/Reports/39466 and http://www.epa.gov/office.html).

Finding 1.2: High early-evening lighting

Description: As observed by the chief engineer, interior lights are on longer hours than needed.

Implications: Early evening lighting energy use is higher than necessary, and could be cut by about 0.3 W/sqft during early evenings. If this level of lighting power were cut during work evenings by four hours, these savings are equivalent to about:

0.3 W/sqft * 98,000 sqft * 1000 hours/year * $0.10/kWh) = $2940/year

Not only will this save energy, it will reduce cooling loads.

Costs to implement this change are negligible assuming janitorial assistance.

Recommendation: Develop an information campaign for tenants or janitors to turn off unneeded lighting.

2. Chillers

Finding 2.1: Retrofit chillers and include a 100-ton chiller

Description: Both chillers one and two operate at about 0.8 kW/ton and spend the majority of hours under 100 tons.

Implications: 120-ton screw chillers are available that operate at about 0.67 kW/ton. A rough estimate of energy savings is then:

100 tons * 2000 hours * 0.13 kW/ton * $0.10/kWh = $2600/year

There will also be significant pumping and cooling tower savings with a smaller chiller.

A 120-ton screw chiller is about $30,000, but this purchase may be warranted given interest in replacing the existing chillers which are reaching the end of their life.

Recommendation: Explore retrofit options more thoroughly using measured cooling load data.

3. Cooling tower

Finding 3.1: Lower condenser water temperature

Description: The condenser receives water between 72 and 75 degrees F from the cooling towers. During high-load days, the towers run full out, but during low-load days they cycle frequently. A lower condenser water temperature would reduce chiller energy use and reduce cycling. The existing chillers can operate with condenser water temperatures as low as 55 degrees F (this has been verified with the manufacturer).

Implications: The rule of thumb is: there is a 1.2-percent degradation in chiller efficiency with every one degree of condenser water temperature. A 10 degree F change in condenser water translates to a 12-percent improvement in chiller efficiency. We verified this relation with actual data from Chiller Two, identifying a one-percent degradation in efficiency with each change in condenser temperature.

100 tons * 2000 hours * 0.1 kW/ton * $0.10/kWh = $2000/year

Costs to implement are negligible.

Recommendation: Reduce the condenser set point to 62 degrees F. This may require the VFD retrofit described in **Finding 3.3**, but could be experimented with to improve the chiller efficiency.

Finding 3.2: Run cooling tower water without fans

Description: The cooling towers could be used to provide some natural cooling from convection without the fans. This strategy would be useful on mild days when the towers cycle frequently under current operation.

Implications: A rough energy savings estimate is as follows:

20 hp * 0.746 kW/hp * 750 hours/year * $0.10/kWh = $1119/year

Not only will this reduce fan energy, but extend equipment life.

Recommendation Experiment with running the water in both tower cells without the fans. Examine the cooling provided and the resulting condenser supply temperature.

Finding 3.3: Install VFD's on cooling towers

Description: The cooling towers are cycling on load days and only one cell is used at a time. The use of variable frequency drives would greatly improve the ability to fit the tower fan use to the load. This would reduce cycling, which is not good for the fans or the chiller, and significantly reduce fan energy use.

Implications: The use of VFD's on the cooling tower has two effects. First, it could cut tower fan energy. Currently there is one 20-horsepower (hp) fan. With a VFD, average operation would involve using both fans with the VFD's, or: 2 * 20 hp * $(0.5)^{3}$ = 5 hp. Annual savings are thus about :

15 hp * 0.746 kW/hp * 2000 hours/year * $0.10/sqft = $2238/year

Part of the savings would come from running both cooling tower fans, and providing a lower condenser set point than is currently available. The VFD may be a necessary element to achieve the energy savings outlined in **Finding: 3.1.**

A VFD retrofit will require about $2500 for each VFD and another $2500 for the installation of each, or $10,000.

Recommendation: Explore possibility of VFD retrofit in relation to other cooling tower strategies presented**.**

Finding 3.4: Reduce condenser-side pressure drop

Description: The rated flow for the condenser is 615 gallons per minute (gpm). Chiller Two condenser flow is about 500 gpm and Chiller One, 530 gpm.

Implications: The reduced flow reduces the condenser heat transfer. Increasing flow would improve the condenser performance and chiller efficiency. We estimate that the chiller performance suffers by about 0.05 kW/ton, or

100 tons * 3000 hours * 0.05 kW/ton * $0.10/kWh = $1000/year

Recommendation: Check to ensure that all balancing valves are open and check valves move freely. Check that condenser tubes are clean.

4. Pumps

Finding 4.1: Reduce use of two chilled water supply pumps together

Description: Two chilled water pumps are occasionally used with one chiller.

Implications: This operation dilutes the chilled water supply temperature and results in higher than needed pump and fan energy. We found about 45 hours of two pumps with one chiller on during the last few months of monitoring. Annual occurrence is probably 50 percent greater or so. While this condition does not appear often, it does result in significant energy losses when in use. These losses can be estimated as follows:

67.5 hours * 20 hp *   kW/hp * $0.10/kWh = $101

Fan and chiller energy is also impacted since these equipment need to run longer hours than they should during such conditions. Thus, additional savings are:

25 hours * 175 hp * 0.746 kW/hp * $0.10/kWh = $326

80 tons * 1 kW/ton * 25 hours * $0.10/kWh = $200

Recommendation: Do not run two pumps with one chiller

Finding 4.2: Trim chilled water pump impellers

Description: The chillers are rated for 450 gpm. Chillers one and two currently operate at about 580 gpm. The pump impellers should be trimmed to reduce the flow and energy use.

Implications: The pumps consume about 7.5 kW each. The energy savings from trimming the impellers is as follows:

$(450/580)^{3}$ * 7.5 kW/pump * 2000 hours/year * $0.10/kWh = $701/year

Cost is about $500 per pump.

Recommendation: Trim pump impellers to achieve rated flow through chillers.

5. Fans

Finding 5.1: Modify ducting to change return fan to be used as exhaust fan

Description: The current fan system uses a return fan instead of an exhaust fan. Significant energy savings could be available if the system was modified to allow the return fan to be used as an exhaust fan. This analysis should also include examining the opportunity to change the filters and silencers used in the supply fan area.

Implications: A ballpark estimate for fan energy savings from the modification of the return air fan is as follows:

50 hp * 0.746 kW/hp * 6000 hours/year * $0.10/kWh = $22,380/year

Recommendation: A comprehensive retrofit should be evaluated, which could also include changing the filter system on the supply fan to include a pre-filter to catch any large debris, followed by cartridge filters. This would lower the pressure drop and reduce fan energy. The silencers in the air distribution system may be more extensive than necessary. The pressure drop from the silencers should be measured and evaluated.

Finding 5.2: Tune VFD operation on supply fans and return fans

Description: Glen and Fred have been examining the use of the VFD's on the supply and return fans and have reported that the VFD's are not being used in an optimal fashion. We are happy to assist in debugging the operational problems that appear to be defeating the energy savings from the VFD's.
Implications: A ballpark estimate of savings from using the VFD's to achieve a 10 percent reduction in flow suggests power savings related to the savings in flow, cubed, or:
$(0.9)^3$ * 75 hp * 0.746 kW/hp * 3000 hours/year * $0.10/kWh = $12,236/year
Recommendation: Needs further review

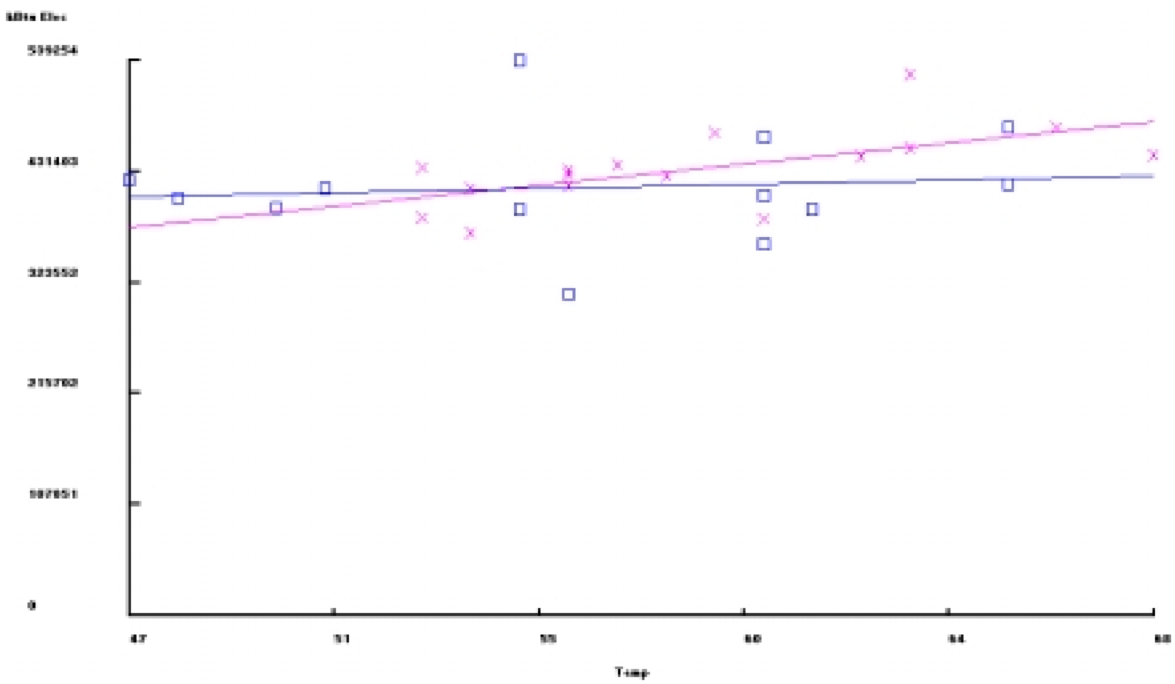
Summary of findings	Type*	One-time cost to implement ($)	Annual energy savings (kWh/yr)	Annual cost savings ($/yr)
1. Lighting and plug loads				
1.1 High nighttime plug loads	O&M	0	68,600	6860
1.2 High early evening lighting	O&M	0	29,400	2940
2. Chillers				
2.1 Retrofit chillers w/ 100-ton chiller	R	30,000	26,000	2600
3. Cooling tower				
3.1 Lower condenser water temperature	O&M	0	20,000	2000
3.2 Run cooling tower water without fans	O&M	0	11,190	1119
3.3 Install VFD's on cooling towers	R	10,000	22,380	2238
3.4 Reduce condenser side pressure drop	O&M	0	10,000	1000
4. Pumps				
4.1 Run one chilled water supply pump	O&M	0	6270	627
4.2 Trim chilled water pump impellers	O&M	1000	7010	701
5. Fans				
5.1 Modify duct/return to exhaust fan	R	50,000	223,800	22,380
5.2 Tune VFD on supply & return fans	O&M	0	122,360	12,236
Totals				
***O&M - Low cost change & O&M**	O&M	1000	274,830	27,483
***R- Retrofits**	R	90,000	272,180	27,218

Appendix II

Whole-building energy use analysis

The IMDS began collecting data on May 1, 1998. The only energy consumption data available for the building before that date are from utility bills, so we used these bills to evaluate whether there have been energy savings since the IMDS was installed. Data from January 1997 through June 1999 were used. Data are available from 1991; however, for comparison, only the previous year was used, to reduce the effect of significant changes in occupancy, the conversion to VAV, and changes in the use of the building. The number of days in each billing cycle is not known, so data are not normalized, which might have smoothed some of the variation. Although the system was not used much for several months after the installation, we used the installation date (May 1, 1998) as a change point. Temperature data was averaged from University of Dayton's daily temperature archive located at http://www.engr.udayton.edu/faculty/jkissock/weather/ for the city of San Francisco.
Figures II-1 through **II-3** show regressions for the two time periods for total monthly electricity (kBtu; thousand British thermal units) and steam (kBtu) versus average outside air temperature (degree F). These regressions were performed in Emodel©, an analysis software that also calculates energy savings for retrofits.

Electricity



Jan 97 to May 98

R2 = 0.37; CV-RMSE = 6.9%

p = 0.12 DW = 1.72 (p=0)

Jun 98 to Jun 99

R2 = 0.01; CV-RMSE = 13.7%

p = -0.08 DW = 2.04 (p=0)

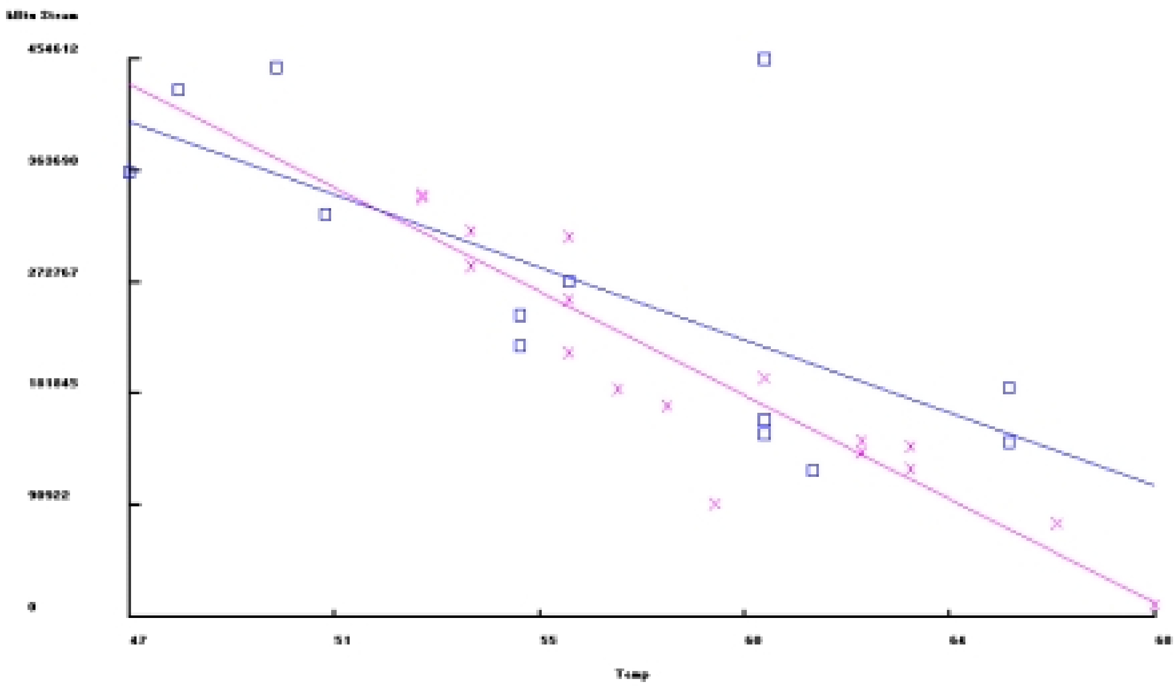
Savings calculations for Model: Multi-group SLR. kBtu Elec vs. Temp (January 1997 to June 1999)

Baseline = 5504664   Measured = 5406549   Avg Savings =7547.315 +- 28170.84 (i.e. +- 373.26%)

Figure II-1. Monthly electricity (kBtu) versus average outside temperature (degree F)

The baseline period shows a modest correlation with temperature, while the post-installation period shows none. See the Phase Two report (Piette, et. al., 1998) for further discussion of the baseline data. The savings calculation indicates that 7547 kBtu were saved every month between June 1998 and June 1999; however, the uncertainty is so large, it is impossible to say if there has been any change at all.

Steam



Jan 97 to May 98

R2 = 0.86; CV-RMSE = 19.8%

p = -0.10 DW = 2.05 (p=0)

Jun 98 to Jun 99

R2 = 0.49; CV-RMSE = 33.4%

p = 0.27 DW = 1.13 (i%)

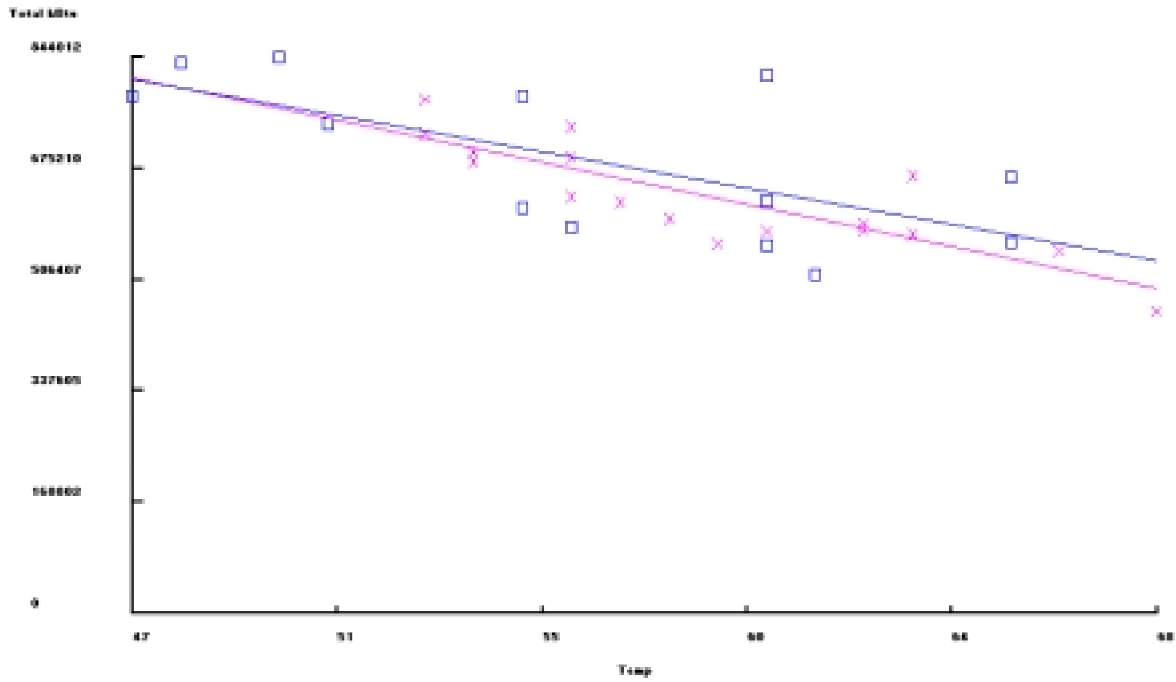
Savings calculations for Model: Multi-group SLR. kBtu Steam vs. Temp

Baseline = 3191723   Measured = 3524166 Avg savings =-25572.574 +- 29806.77 (i.e. +- 116.56%)

Figure II-2. Monthly steam (kBtu) versus average outside temperature (degree F)

The lesser quality of the fit of the regression line in the post-installation case compared to the pre-installation period is due to the single extreme outlier, which also affects the energy savings. This could be due to non-normalized data. The savings calculation for steam is negative, indicating that more steam energy has been used since the IMDS was installed; however, once again, the uncertainty is greater than 100 percent, making it impossible to determine if there was any change. Although steam is not measured by the IMDS, there is still an opportunity to save energy on steam. Steam data may be incorporated at a later date or in future implementations.

Total building energy



Jan 97 to May 98 Jun 98 to Jun 99

R2 = 0.72; CV-RMSE = 7.1% **R2 = 0.45; CV-RMSE = 13.3%**

p = -0.34 DW = 2.60 (p=0) **p = -0.33 DW = 2.03 (p=0)**

Savings calculations for Model: Multi-group SLR. kBtu Total vs. Temp

Baseline = 8696386 Measured = 8930716 Avg savings =-18025.356 +- 27481.28 (i.e. +- 152.46%)

Figure II-3. Monthly total energy (kBtu) versus outside temperature (degree F)

As seen above, both the pre-installation and post-installation models seem reasonably good; however, the savings calculations have such great uncertainty. We conclude that the IMDS has not resulted in any significant energy savings to date.

Total energy use from 1991 through 1998 is shown in **Figure II-4**. This shows that energy use has been changing significantly over the years. Electricity use was slightly down in 1998, but steam increased. This increase was primarily related to weather. As shown above, however, there is little statistically significant difference in energy use from 1997 to 1998.

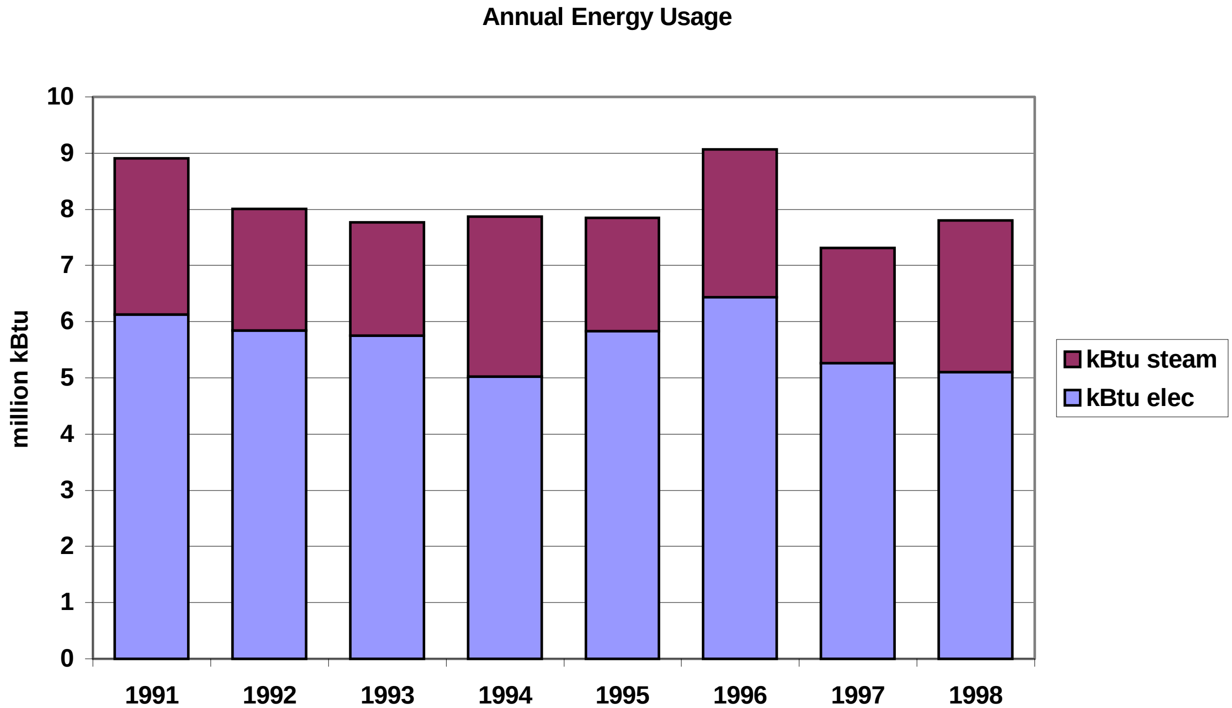


Figure II-4. Multi-year whole-building energy use